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Engineering the System and Technical Integration

J.C. Blair, R.S. Ryan, and L.A. Schutzenhofer
AI Signal Research, Inc., Huntsville, Alabama

Prepared for Marshall Space Flight Center
under Contract NNM07AA77C

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Space Administration

Marshall Space Flight Center • Huntsville, Alabama 35812

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PREFACE

The purpose of this Contractor Report (CR) is to present a model for 'Engineering the System and Technical Integration.' Aspects of the model draw information from several of our other publications and from other sources, which is necessary for completeness. Therefore, this CR contains material that is intentionally repeated in summary form from these sources. The sources are referenced for those who want to probe deeper into the subject.

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LIST OF ACRONYMS, SYMBOLS, AND ABBREVIATIONS

CDR	Critical Design Review
CEV	Crew Exploration Vehicle
CFD	Computational Fluid Dynamics
cg or CG	Center of Gravity
CPU	Central Processing Unit
ΔV	Change in Velocity
DOL	Day of Launch
ECLSS	Environmental Control and Life Support System
EDS	Earth Departure Stage
EMR	Electro Magnetic Radiation
FSW	Flight Software
GLOW	Gross Liftoff Weight
GN&C	Guidance, Navigation, and Control
GSE	Government Supplied Equipment
H/W	Hardware
ICD	Interface Control Document
IFLR	In-Flight Load Relief
INCOSE	Internal Council of Systems Engineering
IPT	Integrated Product Team
Isp	Specific Impulse
I&T	Integration and Test
LAS	Launch Abort System
LCE	Loads Combination Equation
MPS	Main Propulsion System
MR	Mixture Ratio
MSFC	Marshall Space Flight Center
NASA	National Aeronautics and Space Administration
NPR	NASA Procedural Requirement

LIST OF ACRONYMS, SYMBOLS, AND ABBREVIATIONS (Continued)

OMS	Orbital Maneuvering System
P_C	Chamber Pressure
PDF	Probability Density Function
PDR	Preliminary Design Review
PPMD	Program and Project Manager Development
PRA	Probabilistic Risk Assessment
PRSD	Power Reactant Storage and Distribution
q-alpha, q-beta	Dynamic Pressure Times Angle of Attack or Side Slip Angle
RCS	Reaction Control System
RF	Radio Frequency
RSS	Root Sum Square
S/C	Software/Computer
SLaTS	Space Launch and Transportation Systems
S&MA	Safety and Mission Assurance
SN	Stress, Number of Cycles
SRB	Solid Rocket Booster
SRM	Solid Rocket Motor
SR&QA	Safety, Reliability and Quality Assurance
SSF	Second Stage Flight
SSME	Space Shuttle Main Engine
STEL	Static Elastic
STR/Mech	Structures and Mechanisms
STS	Space Transportation System
S/W	Software
TPM	Technical Performance Measures
TPS	Thermal Protection System
TRL	Technology Readiness Level
TSPT	Time Space Position Tracking
TVC	Thrust Vector Control
VAB	Vehicle Assembly Building

CONTRACTOR REPORT

ENGINEERING THE SYSTEM AND TECHNICAL INTEGRATION

I. Introduction

Space exploration is very challenging. Meeting the challenge requires extremely high performance systems that are complex, with interactions that are very difficult to predict. A major lesson we have learned is that *80% of the problems that have occurred are not due to a lack of understanding of the primary engineering disciplines of the system and subsystems, but are due to a breakdown in* ***Engineering the System and Technical Integration.*** *Said in a different context, it is a breakdown in communications*. From a unpublished white paper edited by Dr. Wiley Larson: "*Complex systems typically fail because of the unintended consequences of their design.*" [Larson, et. al, "The Art and Science of Systems Engineering"]. We must therefore understand that everything acts as a system; nothing acts independently; it is a whole, where all the parts interact, many times in unexpected and unpredicted ways. The question faced is "How do we understand and manage these complex, highly interactive systems".

This report will make a cursory look at the various elements of how programs and projects understand and manage engineering the system and technical integration. Considered first is the challenge of space flight and the major lessons learned while meeting the challenge. The report then discusses the process of how we accomplish a total design and operation of a space system with primary emphasis on launch vehicle systems. The major thrust of the report is: *Design and operation of a space project is a total system*. It must have proper attention to integration in all aspects of its characteristics and the processes used, including leadership and management, in order to achieve a balanced and successful project. The balanced system is always a compromise between conflicting requirements and paradoxes that must design the system to preclude all potential failure modes within the operating conditions while carrying out of the functions of the system. Robust communications is one of the keys to the process, as is the evolving of derived requirements as the system and its subsystems interact to perform the mission. Many of the principles and illustrations shown herein are extracted from the handouts of the courses we teach for MSFC: Space Launch and Transportation Systems (SLaTS) and Lessons Learned in Engineering. [Blair, Ryan, and Schutzenhofer, 2011] Other detailed information can be found in other publications as referenced.

II. The Challenge of Space Flight / Meeting the Challenge

A. The Challenge

The physics of flying into space demands that maximum energy be extracted from the chemical energy source, that light but high strength structures be developed, and that the system and element losses be minimized. The transformation from potential energy to kinetic energy pushes the limits of current propulsion system technologies. The same is true for the efficiency of the structure or dry mass of the system. In addition losses that occur in terms of how we fly the system must be stringently managed and controlled. In other words we can just barely make orbit with the technologies available today. These factors result in a requirement for high performance, high power density systems that drive large sensitivities and unwanted interactions. At the same time we must preclude failures in the system while carrying out its major functions and missions. [Blair, Ryan, Schutzenhofer,and Humphries, 2001.]

As a result space launch vehicles must have high performance that drives complex interactions, and pushes the limits of our knowledge and the application of basic physics principles. As Dr. Rick Fleeter so eloquently pointed out [Fleeter, 1998], “A very wise professor of mine once proved the existence of God. He explained that if you look at the energy required to get into earth orbit, a function of the earth’s mass and the gravitational constant, and compare it with the energy of chemical bonds which break and remake to create rocket propulsion, it turns out to be just barely enough to get into orbit. Slightly weaker chemical bonds or a deeper gravity well and we’d be locked down upon earth’s surface. Slightly weaker gravity or tighter molecules and going into orbit could be as easy as “launching” a Cessna 150. Only a God interested in challenging us could have engineered the improbable circumstance of barely possible space travel (When I said this professor was very wise I wasn’t kidding).”

Current technology just barely enables us to make orbit. In other words we must have very efficient propulsion and structural systems and understand and manage all the system losses at a very high proficiency. We have seen in the past that a propulsion system or structural system technology advancement shows great promise of increasing the efficiencies, lowering cost and compressing schedule, yet when integrated into the system it produces interactions that greatly reduce the expected gains. In general the introductions of these more efficient technologies also increase cost and schedules, just the opposite of what is desired. In addition to meeting the technical challenges is the challenge to meet a reasonable development schedule with affordability/cost efficiencies. The following summarizes the challenge for the launch vehicle with some illustrations of the magnitude of the efficiency of the various elements. [Blair, Ryan, and Schutzenhofer, (SLaTS Course), 2010]

Launch vehicle design is a challenge of highest order

- Payload size and mass drive launch vehicle performance requirements.
- The vehicle must impart orbital energy to the payload.
  (Orbital energy is large --- for~160 n.m. altitude, ΔV ~25,300 ft/s)

- With current technology, this pushes propulsion, structures, materials, and systems capability to the limit.
- Affordability with schedule efficiency impose additional challenges.

For example:

Propulsion:

- Efficient conversion of chemical potential energy to kinetic energy (The Space Shuttle Main Engine has an I_{sp} of 452s out of a potential of about 460s. If the Shuttle system was designed for 460s, this change would result in a 25% growth in the fuel tank volume. Thus, an I_{sp} of 460s would not result in a vehicle providing maximum payload capability.)

- Thrust to weight ratio at liftoff greater than 1.1. To obtain this thrust level The Saturn F-1 engine chamber pressure is P_c=1000psi; The Space Shuttle Main Engine (SSME) chamber pressure is P_c=3000psi. The increase in chamber pressure of the SSME over the F-1 increases the static/dynamic flow induced loads by at least a factor of three.

- Figure 1 puts the challenge in perspective by comparing the power density of common transportation engines with the Space Shuttle Main Engine (SSME). Plotted is horsepower per pound for an auto engine, Indy Race Car Engine, Small Jet Engine, Large Jet Engine and the SSME. Notice that the car engine has a ratio of 0.54 while the SSME has a ratio of 879. If an average car engine could be built to the same power density and efficiency as the SSME it would weigh about 1/4 of a pound.

Structures:

- Efficient (lightweight and strong) structures result in a vehicle mass fraction of around 0.90 (the ratio of propellant to total mass). For example the ratio of the average skin thickness to the diameter of the Shuttle External Tank is a factor of 3 less than that of an aluminum drink can.

System Effects:

- Losses during mission must be minimized (Understand, quantify, control, and manage). The main source of the losses is the presence of complex interactions which have their source in the high performance requirements.

In addition to the challenges delineated above the system is further challenged by the following considerations and activities:

- Precluding failure of the system and subsystems while carrying out their functions and missions (Constant emphasis on identification of failure modes and their mitigation). As

Dr. Henry Petroski has said, “The best way to prevent failure is to understand failure.” [Petroski, 2008]

- Integrating schedule efficiency and affordability/cost into the technical issues stated above, thus balancing the total system. The balancing is a compromise between conflicting requirements.

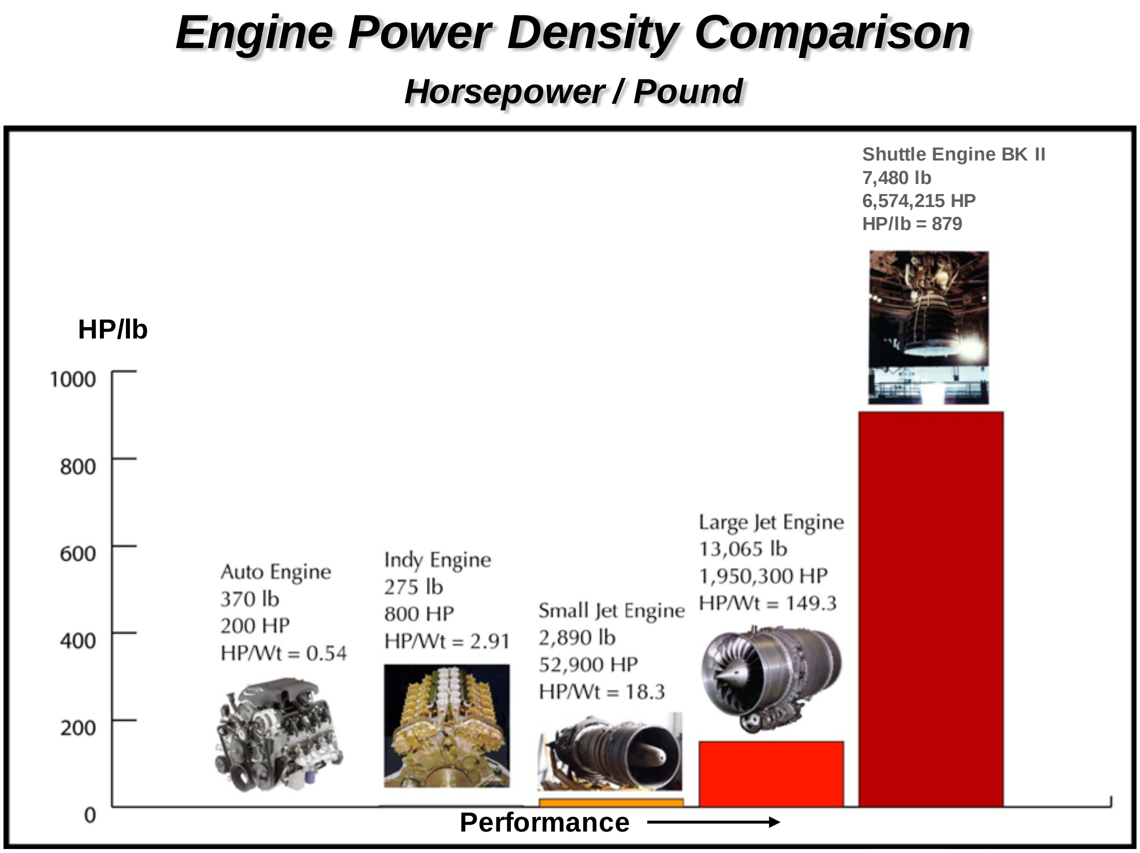


Figure 1: Power Density Comparison of Transportation Systems Engines
[SLaTS Course, Chapter 1, 2010]

All of this high power density and high efficiency comes with a price. There are many problems that occurred in the SSME that can be shown to be a direct result of the high performance requirement. The basic characteristics of the fuel turbopump illustrate these high power density requirements. For example the turbine blades that power the pump are about the size of one’s thumb, yet during peak performance times each turbine blade generates about 550 horsepower, which is at least twice the power of an automobile engine. Achieving this performance leads to high temperatures and pressures that present a major challenge to the design and the development of materials that can endure the environments. In addition, complexity is another factor that must be considered in the design of high performance systems. In his book, Robert Pool, [Pool, 1997] says that the complexity factor leads to most of the failures and is very difficult to predict. He also concludes that this results not only in technical complexity, but in organizational complexity as well.

High performance requirements lead to high power densities and large sensitivities. This requires in-depth understanding and intricate balancing of the system to achieve success. The combination of high performance, high power densities, sensitivities, and complexity results in the need for project managers to have a high octane, efficient organization.

The application of the principles of Engineering the System and Technical Integration results in constant need for decision making. These decisions have impacts throughout the total project life cycle. The following are some quotes that deal with decisions that entail the sensitivities, interactions, and failure modes.

- "When you put energy into a system you can never choose what kind of changes shall take place and what kind of results remain. All you can do, and that only within limits, is to regulate the amounts of the various changes. This you do by design" [Pye, 1969]
- "The requirements for design conflict and cannot be reconciled. All designs for devices are some degree failures…The designer or his client has to choose to what degree and where there shall be failures." [Pye, 1969]
- "All structures will be broken or destroyed in the end. Just as all people will die in the end. It is the purpose of medicine and engineering to postpone these occurrences for a decent interval. The question is: What is to be regarded as a decent interval?'" [Gordon, 1988]
- "Cooperate with Mother Nature to the maximum extent possible; minimum energy solutions are almost always the most reliable." [Junkins, 2001]
- "To understand what engineering is and what engineers do is to understand how failures can happen and how they can contribute more than successes to advance technology." [Petroski, 2008]

As stated initially the major lesson we have learned in dealing with these high performance systems is: *The problems experienced in meeting the Space Exploration Challenge have not been a breakdown in the understanding of individual disciplines of our work but in a breakdown in the application of* ***Engineering the System and Technical Integration.***

Recently the Deputy Assistant Secretary of the Air Force for Science, Technology, and Engineering asked the National Academies to study the project acquisition failures and make recommendations for solutions. [National Research Council, 2008] Some of the major findings are:

1. The committee believes that the accumulation of processes and controls over the years - well meant of course - has stifled domain-based judgment that is necessary for timely success.
2. The creation of a robust systems engineering process is critically dependent on having experienced systems engineers with adequate knowledge of the domain relevant to a contemplated program.
3. The committee said there were six drivers of cost, development time, and performance risk. They call these factors the six *seeds of failure*. They are
    - Inexperienced leadership

- External interface complexity
- System complexity
- Incomplete or unstable requirements at Milestone B
- Reliance on immature technology
- Reliance on large amounts of new software.

In looking at major failures of NASA systems, five root causes have been identified:

1. Shifting from engineering “hands on” and “excellence” to “insight/oversight”. Lack of ownership.
2. “Normalization of the deviances”. Not questioning anomalies.
3. Lack of critical thinking. Over-reliance on procedures and computer codes.
4. Decentralization of authority.
5. Organizational and technical complexity.

These root causes and recommended remedies are summarized in a later section of the report (Section IV.H, Achieving Engineering Excellence).

B. Meeting the Challenge

Meeting the challenge of space flight includes

- High efficiency propulsion systems
- Dry mass efficiency
- Efficient management of system losses
- Effectively dealing with systems interactions
- Precluding failures
- Affordability/Cost
- Efficient development schedule

These are major issues all aerospace projects are facing in today’s environment and culture. It is mandatory that these systems have a short development time and be affordable. Defining affordability usually means determining how much the political system will appropriate.

Considering the above references and our experiences, the following sections will address what we think is one of the better ways of dealing with the challenge. In general we call the process *Engineering the System* which includes Technical Integration and Classical Systems Engineering.

The challenge can be met using the approach outlined below on Figure 2. Notice that objective of the system has many components of the challenge such as performance, affordability/cost, schedules, and reliability/safety. The challenge is met by balancing the uncertainties, sensitivities, interaction and margins. This balancing of the system is always a compromise between the conflicting requirements, subsystem optimization versus system optimization and many of the derived requirements. The balancing is achieved by having a design process to design the product and an operational process to build and operate the product. This is implemented through leadership and management, which is the enabling framework. Finally the operating foundation of all the processes for meeting the challenge is the triad of integrity, communications and relationships. It should be pointed out that each of these areas comprise sets of major activities, processes and principles within themselves requiring more time and space to address than is possible within this report.

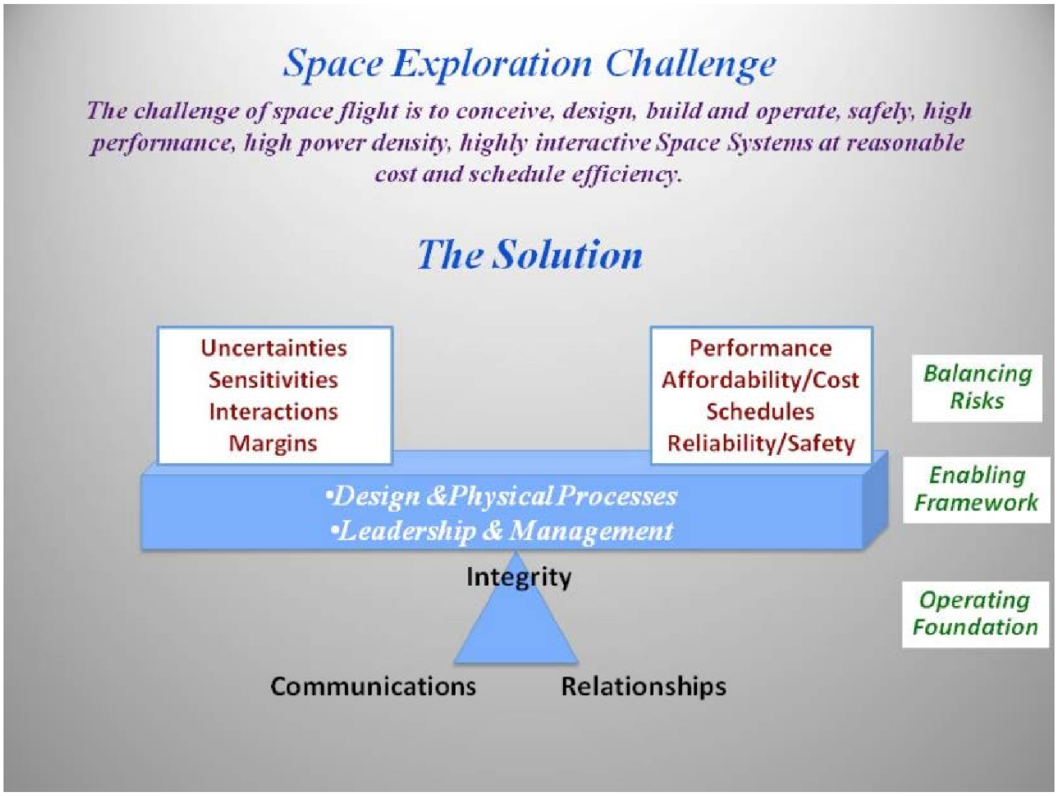


Figure 2. Process for Meeting the Challenge of Space Flight

NASA has published their top level model for Engineering the System as NPR 123.1A focusing on the various program phases [NASA Systems Engineering Process and Requirements, 2007]. Figure 3 is the basic approach showing the relationship between requirements and the realized products. Figure 4 depicts the relationship between the various reviews and the program phases.

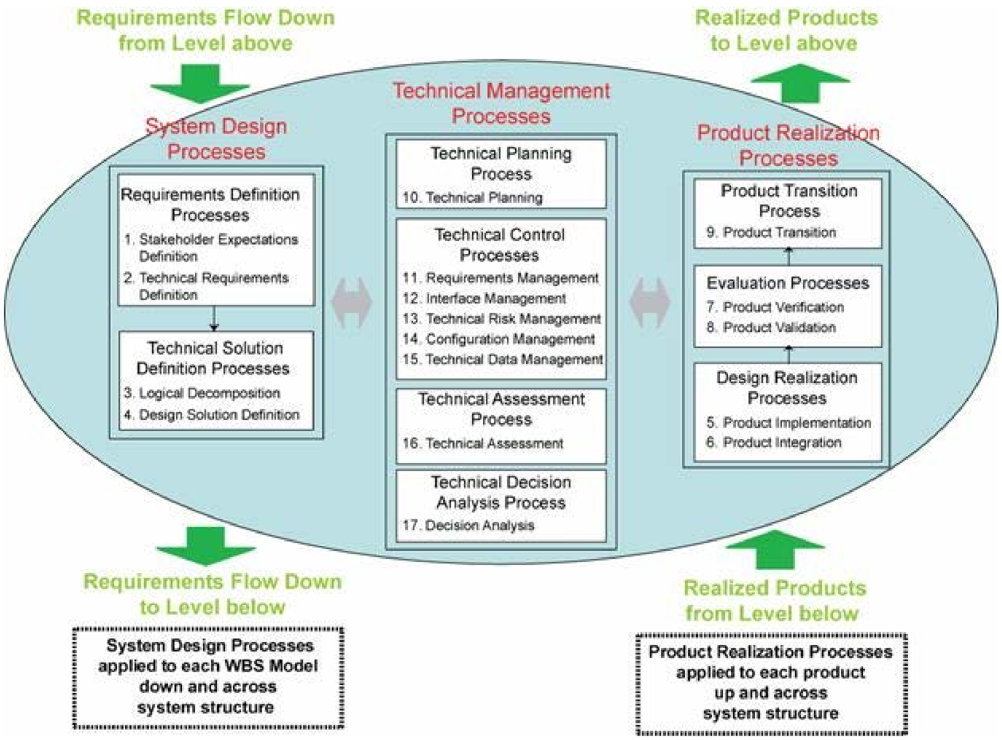


Figure 3. NASA's System Engineering Process
[NASA Systems Engineering Process and Requirements, 2007]

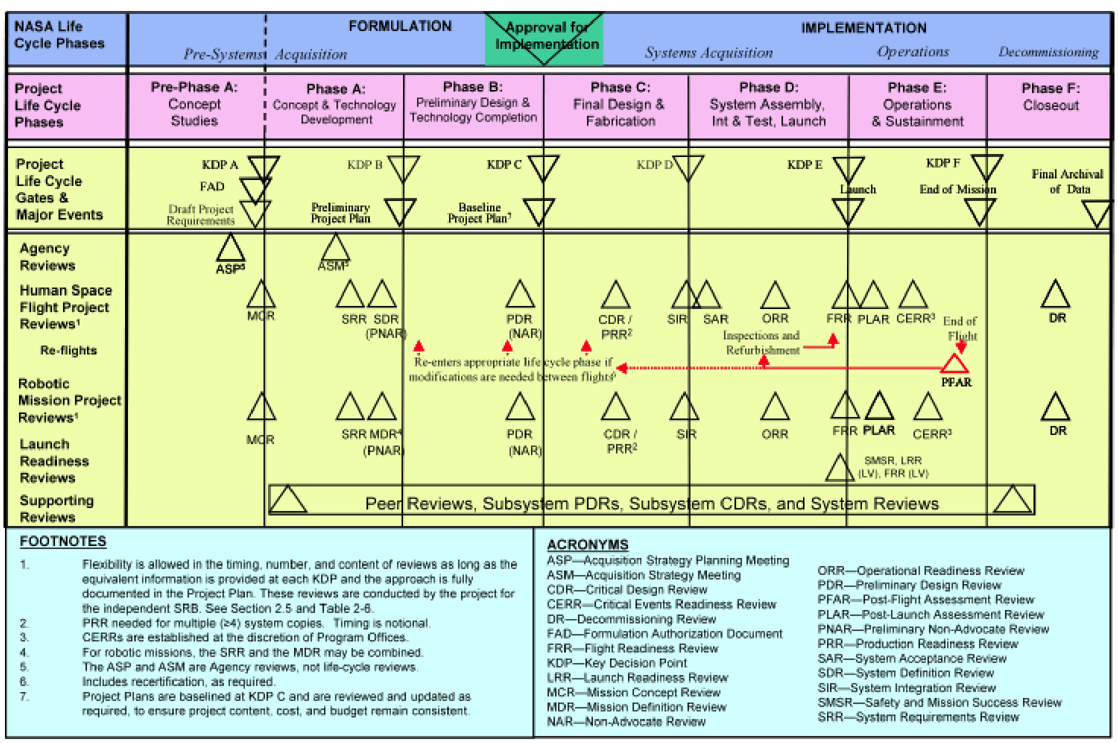


Figure 4. Program Reviews and Product Program Phases
[NASA Systems Engineering Process and Requirements, 2007]

Our model, developed before the initiation of this NASA model, serves as a model for Engineering the System during the Formulation and Implementation Phases. There are many other models such as the Vee and the International Council of Systems Engineering (INCOSE) models that some use for this work. All have some merit and should be studied as an adjunct to our model. The rest of the report will be a discussion of the elements of Figure 2 that a project manager must understand and manage to have a successful product. The organization required to implement these principles and functions takes many forms and depends on the individual project situation therefore it is beyond the scope of this report.

III. Engineering the System

It is the responsibility of the Project Manager to bring about the overall development of a successful product that meets the challenges described above. We call this *Engineering the System.* To set the stage for understanding the *Engineering the System* model we will first look at a typical set of functions a project or program manager must perform. (Figure 5)

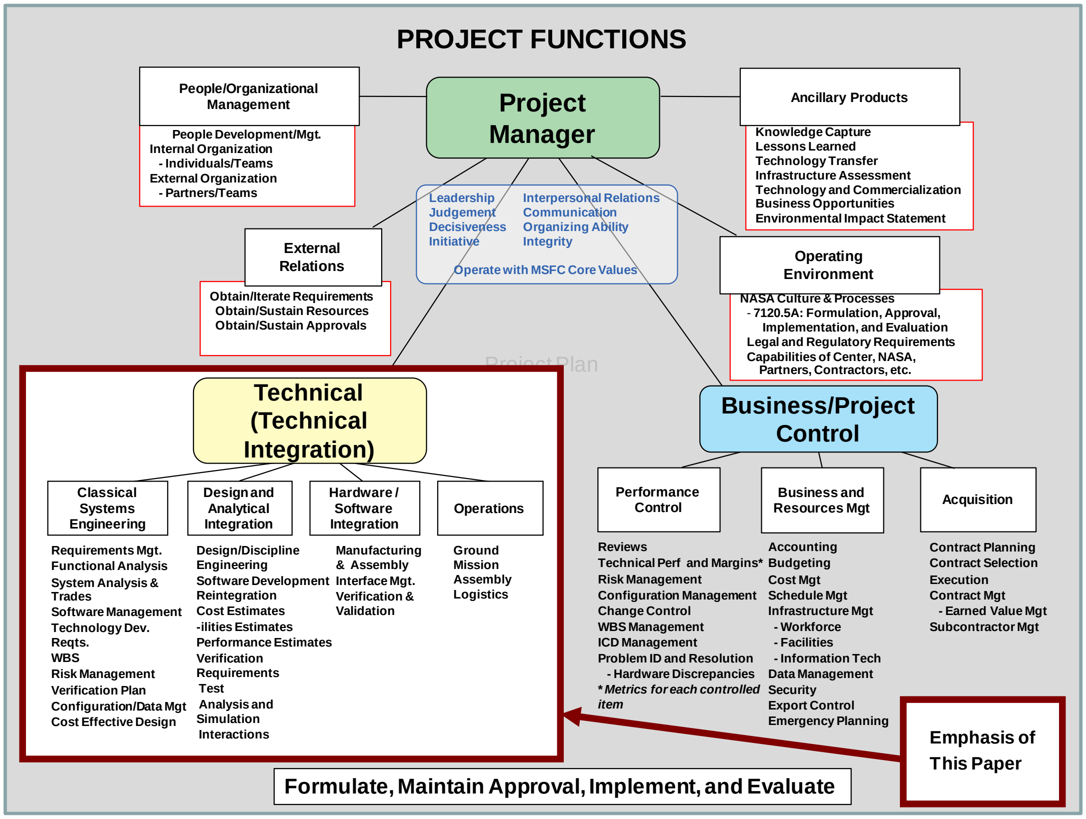


Figure 5. Program or Project Manager's Functions

The functions of a project manager are separated into six main categories: 1. Technical, 2. Business/Project Control, 3. People and Organizational Management, 4. External Relations, 5. Operating Environment, and 6. Ancillary Products. In this report we will mainly deal with the Technical category which contains the function of Technical Integration and is subdivided into (a) Classical Systems Engineering, (b) Design and Analytical Integration, (c) Hardware/Software Integration, and (d) Operations. The following sections will deal with these and other functions from a top-level viewpoint. In summary the project manager must formulate, maintain approval, implement and evaluate across all these functions from both the specialty and the integrated system standpoint.

This report will be primarily concerned with the Technical function; however, proper execution of the Technical function must interact with the Business, External Relations, Operating Environment and other functions to achieve the best balanced technical solution.

A. Technical Integration and Classical Systems Engineering

- Technical Integration is typically the integration of Design and Analysis, Hardware and Software, Operations, and Classical System Engineering along with interactions of Business, External Relations, Operating Environment and other functions to create a system with acceptable performance that is safe, reliable, and affordable.

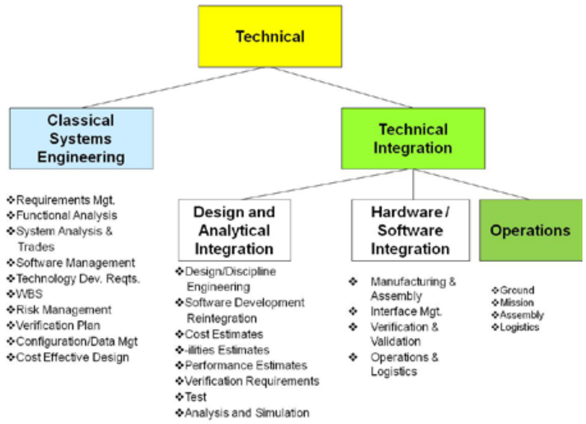
- Classical System Engineering provides the processes, manages the documentation, reviews, and configuration control for the Technical Integration function.

The typical functions of each are:

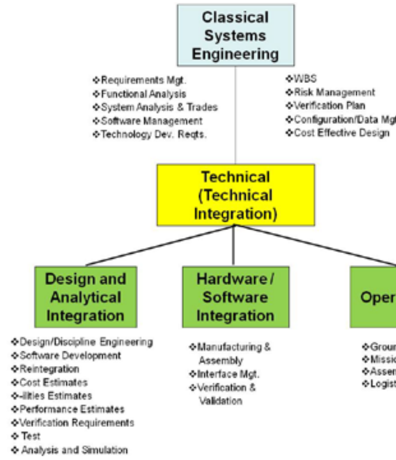
Technical Integration
- Design
- Analysis & Test
- Trade Studies
- Build Hardware
- Develop Software
- Verification & Validation
- Operations
- -ilities

Classical Systems Engineering
- Processes
- Planning
- Requirements Tracking
- Reviews
- Configuration Control
- Verification & Validation Tracking
- Documentation

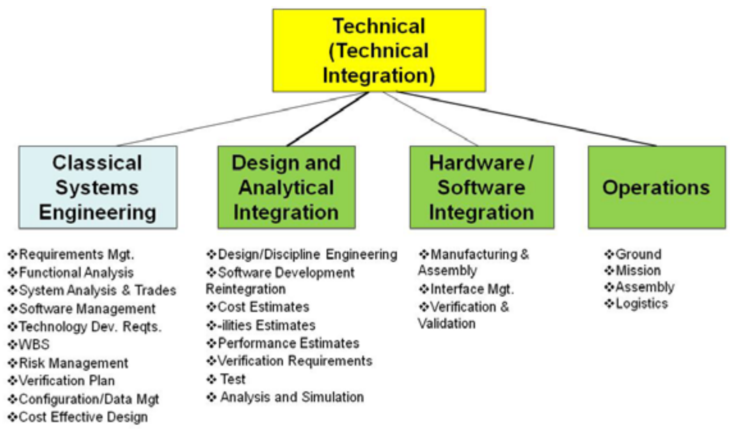
There can be various ways of relating Technical Integration and Classical Systems Engineering, as shown on Figure 6. Figure 6 shows a top-level sketch of some of the models used for integration. In fact what we have observed is that most of these forms of the model create an overemphasis of classical system engineering and de-emphasis of technical integration, sometimes losing it altogether. However, it should be pointed out that any of these models can be made to work with the proper leadership and management making sure that the system process is balanced. We think that the preferred model of Figure 6 best represents the true balance of the technical functions.



Technical Integration Model 1



Technical Integration Model 2



Preferred Technical Integration Model

Figure 6. Technical Integration Models

A similar interpretation is given in Reference [Larson, et. al., 2009] by Schaible, Scolese and Ryschkewitch, who write that, “Systems Engineering is not only about the details of requirements and interfaces among subsystems. …Similarly, accurate control of interfaces and requirements is necessary to good SE, but no amount of care in such matters can make a poor design concept better. Systems engineering is first and foremost about getting the right design - and then about maintaining and enchancing its technical integrity, as well as managing complexity with good processes to get the design right. …For our purpose, we divide SE into technical leadership and its ally, systems management.

- *Technical leadership* focuses on a system’s technical design and technical integrity throughout its lifecycle
- *Systems management* focuses on managing the complexity associated with having many technical disciplines, multiple organizations, and hundreds or thousands of people engaged in a highly technical activity

…To succeed we must blend technical leadership and systems management into complete systems engineering.”

The situation is complicated by the complexity of systems and the compartmentalization done in the design process for design efficiency (to be discussed in more detail in later sections). We in general handle compartmentalization by defining and managing information and interfaces; however, when we reintegrate the parts back into a system, interactions occur which are very difficult to predict. Quoting from Pool, “More importantly, complex systems are not completely predictable. No one knows exactly how a given design will work until it has been built and tested-and the greater the complexity, the more testing it needs. … In truly complex systems, no amount of testing or experience will ever uncover all the possibilities, so decisions about risky technologies become a matter of how much uncertainty one is willing to put up with and how much one trusts the designers.”

“The complexity that marks modern technology is not merely a matter of how many pieces are part of the system. Indeed, that is not even the most important factor. Instead, the defining feature of a complex system is how its parts interact. By contrast, the components of a complex system interact with others, and the actions of any one component may depend upon what others in the system are doing. The more interaction among the components, the more complex the system, and the harder it is to predict what the system will do from knowing how any given components will perform. The more complex a system, the more difficult it is to understand all the different ways the system may behave- and in particular, to anticipate all the different ways it may fail. Interdependence among parts creates entirely new ways that things can go wrong, ways that engineers often overlook or ignore. Thus many technological failures chalked up to mechanical breakdown or design flaws are more accurately described as the children of complexity.” [Pool, 1997]. Our experience parallels Poole’s observations and says that we must manage the interactions as well as the information flow and the interfaces.

Designing complex systems entails many decisions throughout the process. The decisions are always a balancing act composed of trades based on taking some of what you don’t want in order to get some of what you do want. Figure 7 illustrates the process of evolving requirements and design through trades and balancing the system out, which always involves compromise.

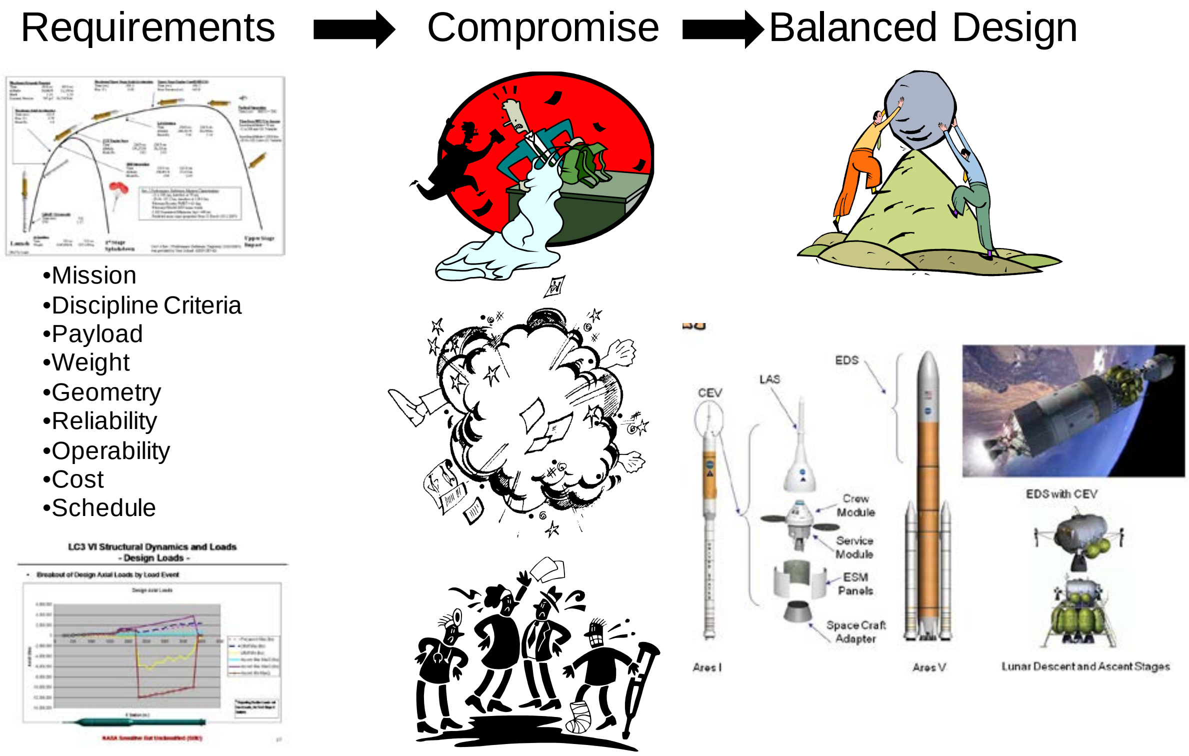


Figure 7: Space System Design is a Compromise

It is imperative that we take a systems design/balancing approach across all aspects of the life cycle. This is necessary in order to meet operability, cost, and other goals in addition to performance. Otherwise the system obtained is driven by performance requirements and the impacts are accepted in the other programmatic areas such as cost, schedule and safety.

The goal we endeavor to meet is: While achieving necessary safety, obtain the best balance among performance, the -ilities, and affordability/cost. The success of a launch system is measured not only by its physical performance parameters such as how much payload it can lift to orbit, but by its reliability, its operability, how much it costs, and numerous other attributes. A successful system must be designed from the start for these "-ilities" and costs as well as for physical performance. To accomplish this goal it is necessary that functional relationships between the parameters of design and the -ilities be established. While it is a challenge to obtain these functional relationships, we must work toward making the –ilities and cost concurrent "design-to" attributes along with performance, as illustrated on Figure 8.

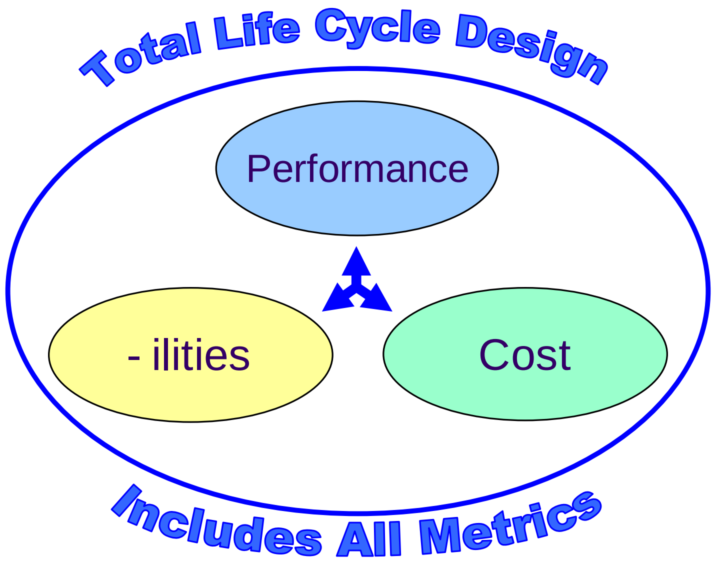


Figure 8. Lifecycle Design from a Systems Viewpoint

B. The Scope of a Project: Lifecycle Awareness Considerations

The first aspect to managing a project requires that the manager and the organizational system have a constant awareness of the lifecycle of the project and where it is in the cycle (Figure 9). The awareness and the resulting management approach must be from a total systems viewpoint. Developing the architectures, refining the concepts, and performing preliminary and detail design is an integrated whole which considers all aspects of the life cycle that then can be implemented during the phases shown on the chart. [The total lifecycle process including the final operating process is sometimes called a *product design*. Alternate terminology designates *design* as the process of producing specifications.]

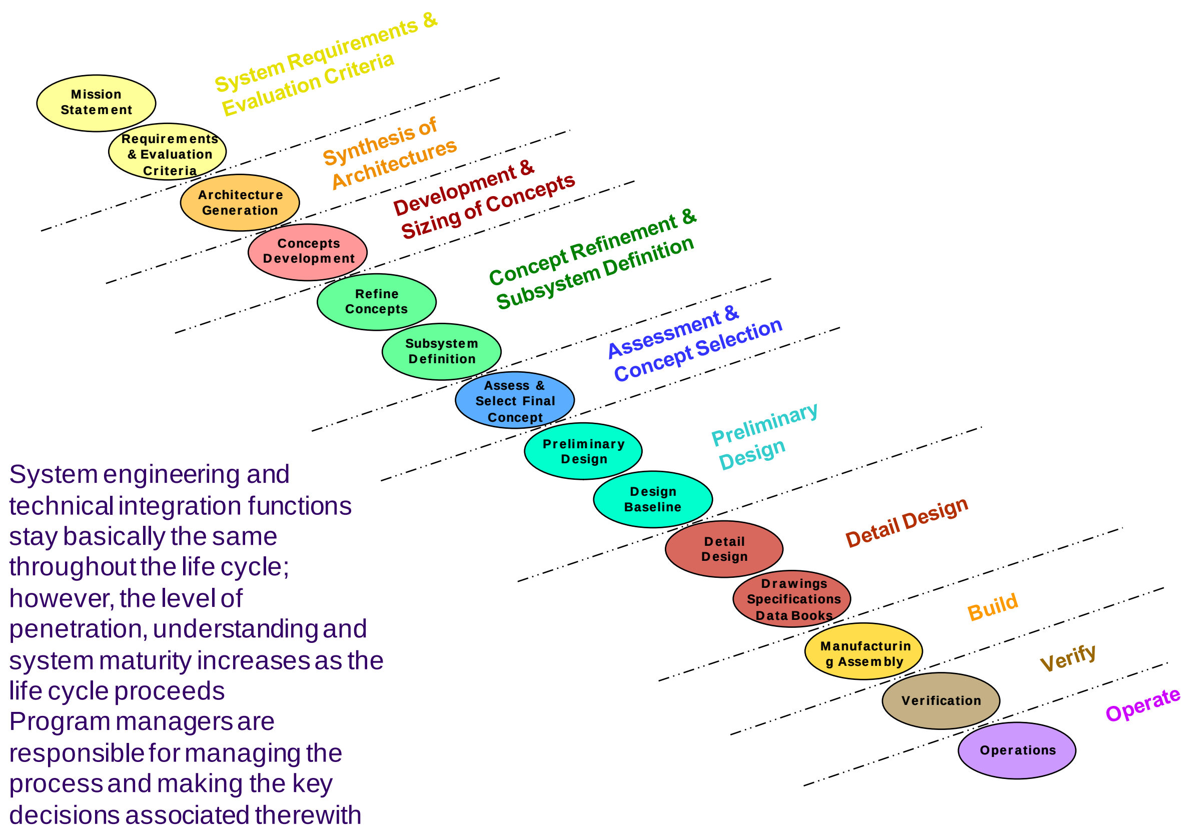


Figure 9: Project Lifecycle Flow

Although Figure 9 depicts the elements of the life cycle progressing in a linear manner, there are many feedback loops and iterations that occur within the process as the design evolves. The main elements of the life cycle are summarized in the following.

1. Requirements

Life cycle starts with requirements of the initial mission objective. Derived from these top-level mission requirements is a set of baseline requirements, designated *derived requirements*. Derived requirements constitute the great majority of the requirements on the project. They must consider the total life cycle and cover all design aspects; therefore their derivation initially is highly iterative but converges to the set of baseline requirements. Requirements decomposition and development of derived requirements are addressed in a later section of the report.

Pugh says that “the requirements are the mantle of the design.” Requirements should be verifiable and must be under strict control by the project. Constraints and requirements must be constantly under review and challenged since they determine what the product will be. As Pugh and others have said, many if not most of the requirements conflict and result in trades, which balance these conflicts in the best manner possible; however in the end you always get some of what you don’t want in order to get most of what you do want. [Pugh, 1994] Figure 10 summarizes these characteristics and show that it is always a major iteration process. One word of caution: make sure the requirements are not so constraining that there is no room left for the creativity of the engineer and designer to determine the best solution.

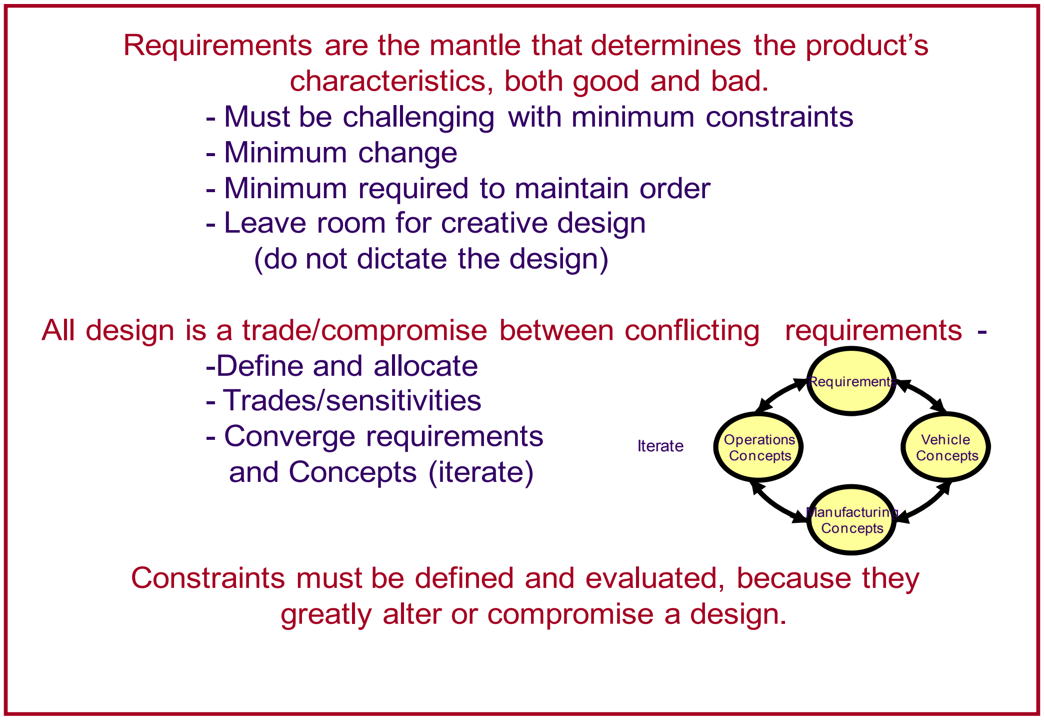


Figure 10. Summary of the Characteristics of Requirements and Constraints

2. Architecture Generation

Using these top level requirements, the various functions the system must perform are determined, from which is derived a group of potential architectures that can perform the functions. These architectures are for the total system and include for a launch system the launch vehicle, payloads, manufacturing, operations, logistics, communications etc. Through a process of evaluation the potential architectures are narrowed down to a handful, for which the concept development and selection process is started.

3. Concept Development and Selection

Concept Development adds detail and fidelity to the candidate architectures to better determine their characteristics and enable an informed down-selection. Initially, mass estimating relationships and sizing programs are used to achieve closure on a configuration. The system and subsystems then are defined in greater detail to meet their requirements considering natural and induced environments. More detailed evaluations lead to the selection of one or more concepts to be carried to Preliminary Design. These concepts are for the total system, including the vehicle design, manufacturing and verification plan, and concept of operations.

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Figure 11 is Pugh's model for the convergence of the concept selection and the balancing of requirements. As you deal with the options of the concept you are also dealing with tailoring the requirements. As this process converges it arrives at the balanced concept and requirements.

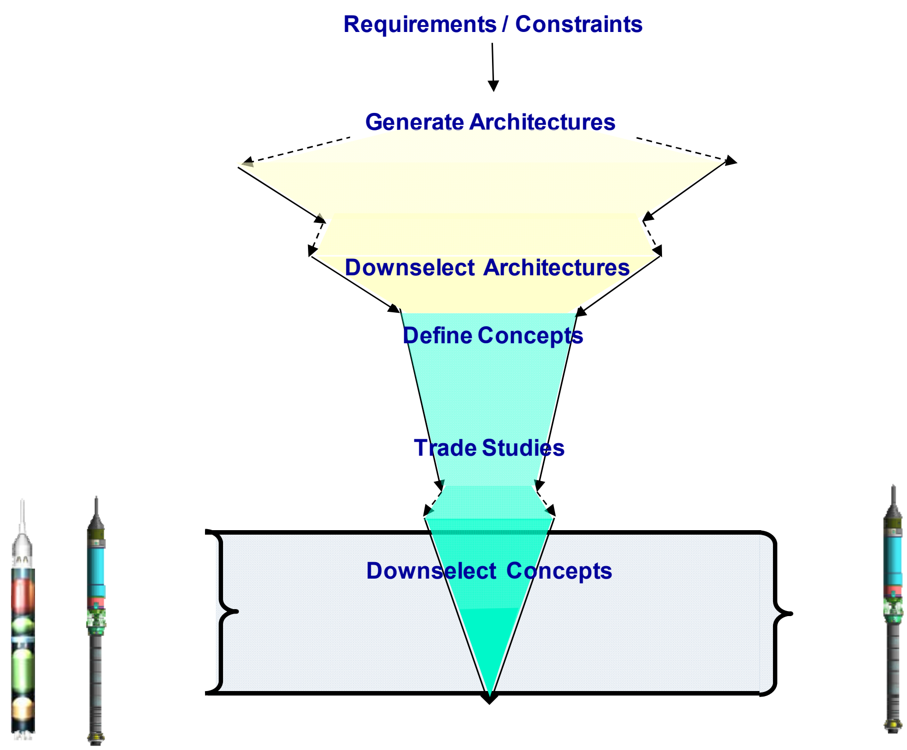


Figure 11. Balancing Requirements and Concepts, Pugh Model
[Pugh, 1994]

4. Preliminary Design Definition

The purpose of preliminary design is to provide greater assurance that the concept is capable of meeting requirements. (In general there is only one concept to carry through preliminary design; however, there are cases where two concepts are carried through the initial part of the PDR phase.) To achieve these results, the fidelity of the configuration is increased and refined; in addition, the significant subsystems and their requirements are defined. The depth of penetration of trade and sensitivity studies is increased through analyses, tests, and simulations. Then the requirements, risk, cost, reliability, safety, operability, schedule, and TRL are refined and reassessed. Interfaces, interactions, pertinent tests, top-level verification plans, and preliminary facility and GSE requirements/concepts are defined and the fidelity of the project plans and documents is updated. Preliminary design can occur in iterations as concepts are down selected following each iteration until the best concept remains. This concept then goes to detail design. At the completion of preliminary design, there is a preliminary design review (PDR). At the completion of PDR, the concept becomes the baseline and is ready for detail design.

5. Detail Design Definition

The purpose of detail design is to provide drawings and specifications for all the hardware and software of the fully analyzed, developmentally tested, and simulated system that can be manufactured and operated within cost and flown with an acceptable risk. The performance, cost, reliability, safety, operability, schedule, and technology readiness attributes of this system must satisfy the mission statement, requirements, and constraints. At the completion of detail design, there is a review called the critical design review (CDR). Additionally, plans are updated for final development, manufacturing, verification, and operations.

6. Materials and Manufacturing

The design properties of a material system are contingent on the manufacturing processes employed, both in the primary production, secondary shaping, and assembly phase. Accordingly, the design functions of materials and manufacturing have been historically linked. Their interdependence in the modern era has been magnified by the rapid expansion in the development of both new materials and new processes.

Composite materials, including metallic, nonmetallic, and combinations thereof, are examples of advanced structural material systems that challenge traditional design methodology. Many such systems require the development of design properties specific to individual component shapes. This differs from most metal alloy systems where the design properties for basic product forms (i.e., sheet, plate, extrusions etc.) are readily available and apply independent of final component shape. When working with advanced structural material systems, it is often necessary to develop the manufacturing processes concurrent with the component design. The result is a “best fit” compromise between part configuration, weight, cost, and schedule. Assembly processes, such as welding and bonding which alter the properties of a material, also require special attention and clearly delineate the synergistic relationship between materials and manufacturing [Blair, Ryan, Schutzenhofer, and Humphries, 2001].

7. Verification and Validation

Verification and validation is one of the key tasks a project manager is responsible for, with the completion of the task providing the information of how well the hardware and software meets the requirements and it worthiness for flight/operations. We normally define verification and validation as:

- **Verification** – Proof, by examination of objective evidence, that the product complies with specifications.
- **Validation** – Proof, by examination of objective evidence, that the product accomplishes the intended purpose and is ready for a particular use.

Verification and Validation may be determined by test, analysis, demonstration, inspection, or a combination of these.

8. Operations

Launch operations can be considered in terms of mission and ground operations. In the following paragraphs is an overview of each.

Mission operations are associated with planning, designing, and executing events for the launch vehicle to achieve mission success. This includes activities associated with prelaunch, launch, in-flight (including abort scenarios), on orbit, de-orbit, entry, landing, and recovery. Included in mission operations are the launch system communication process, as well as astronaut selection and training.

Ground operations entail designing and managing a process that includes activities from transportation to training. Firstly, all major elements of the vehicle are received as transported from the manufacturers. Then each element must be processed to prepare for final vehicle assembly. For past and current NASA vehicles, final vehicle assembly takes place in the vertical assembly building (VAB) where system integration, checkout, and verification are completed. The cargo must be adequately processed with integration into the vehicle either in the VAB or on the pad. The vehicle is rolled out on the mobile launch platform. All of the launch pad facilities supporting the launch must be prepared, e.g. rotating service structure, noise suppression, etc. Then prelaunch operations include propellant loading, launch control center operations (Mission Control Center and Payload Operations Center), etc. In anticipation of post flight, preparations are made for landing, post landing, and depot maintenance. Execution of ground operations requires integrated logistics support and training and certification of key personnel.

The goal throughout these life cycle phases is to conceive, design, build and verify a system, including the operational system, that can be operated in a safe and affordable manner and meet the objectives of the program.

9. Iterations within the Process

Although the Vee is not a part of NASA’s NPR on System Engineering, the following Figure 12 shows a detailed view of the left side of the classical Vee-diagram (amended) and illustrates where the requirements and design in the life cycle are addressed at each phase of the development process. While requirements and design development proceed down the left side of the “Vee”, the interacting issues of all life cycle phases are captured with vertical arrows depicting interactions. The level of fidelity needed will increase as you progress time-wise down the left portion of the “Vee”. Regardless of the model used for technical integration, this penetration must take place.

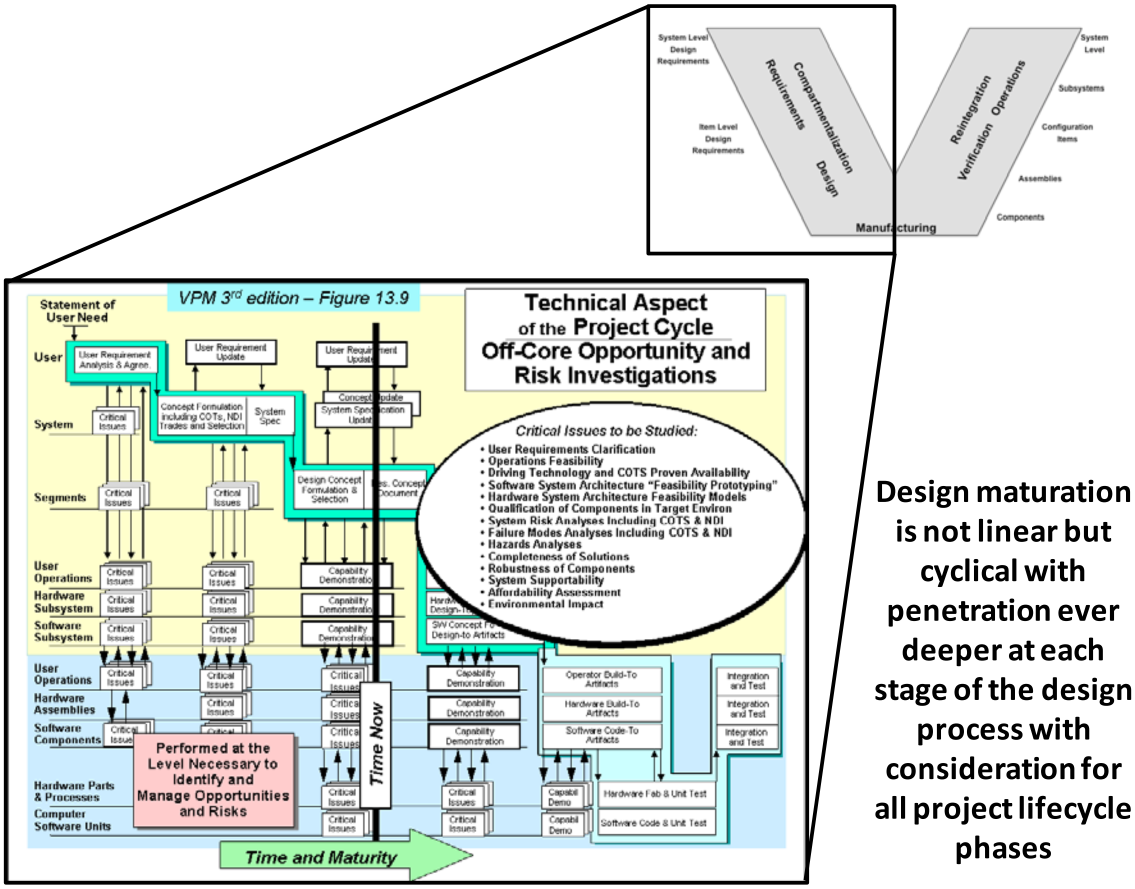


Figure 12. Depth of Penetration and Considerations of Each Phase of the Vee Diagram
[Forsberg, 2005]

10. Mindsets of the Life Cycle Phases

One very interesting aspect of the life cycle that the management team must also be aware of is that the mindset or the culture is different for all the different phases of the life cycle. For example: the phases of formulating, designing, and implementing an operational system each require a very different mindset/culture. Implementing an operating system is, by its nature, process and procedural focused. You must keep building and operating the system to the characteristics for which it was verified, which drives the culture to emphasize procedures and processes. Formulating the system needs much less emphasis on procedures and processes; here the emphasis is on innovation and creativity to conceive, trade and balance a total system for the performance, schedule, and cost of the total life cycle.

Figure 13 shows an amended NASA System Engineering approach [NASA Project Handbook, 2008], with the final phase of validation including initial flight testing and the additional long term phase of operations, which is the E phase of NASA Standards. At the bottom of the chart is shown the general culture characteristics of each of the phases. An important management question this raises is; "How does the organization and culture change to accommodate these different life cycle phases with different functional emphases?" How we manage across these different lifecycle phases is a major challenge, particularly if the proceeding programs were in the operation phases that generated a culture that wants to start the new program with the baggage of all the procedures and processes inherited from the past culture.

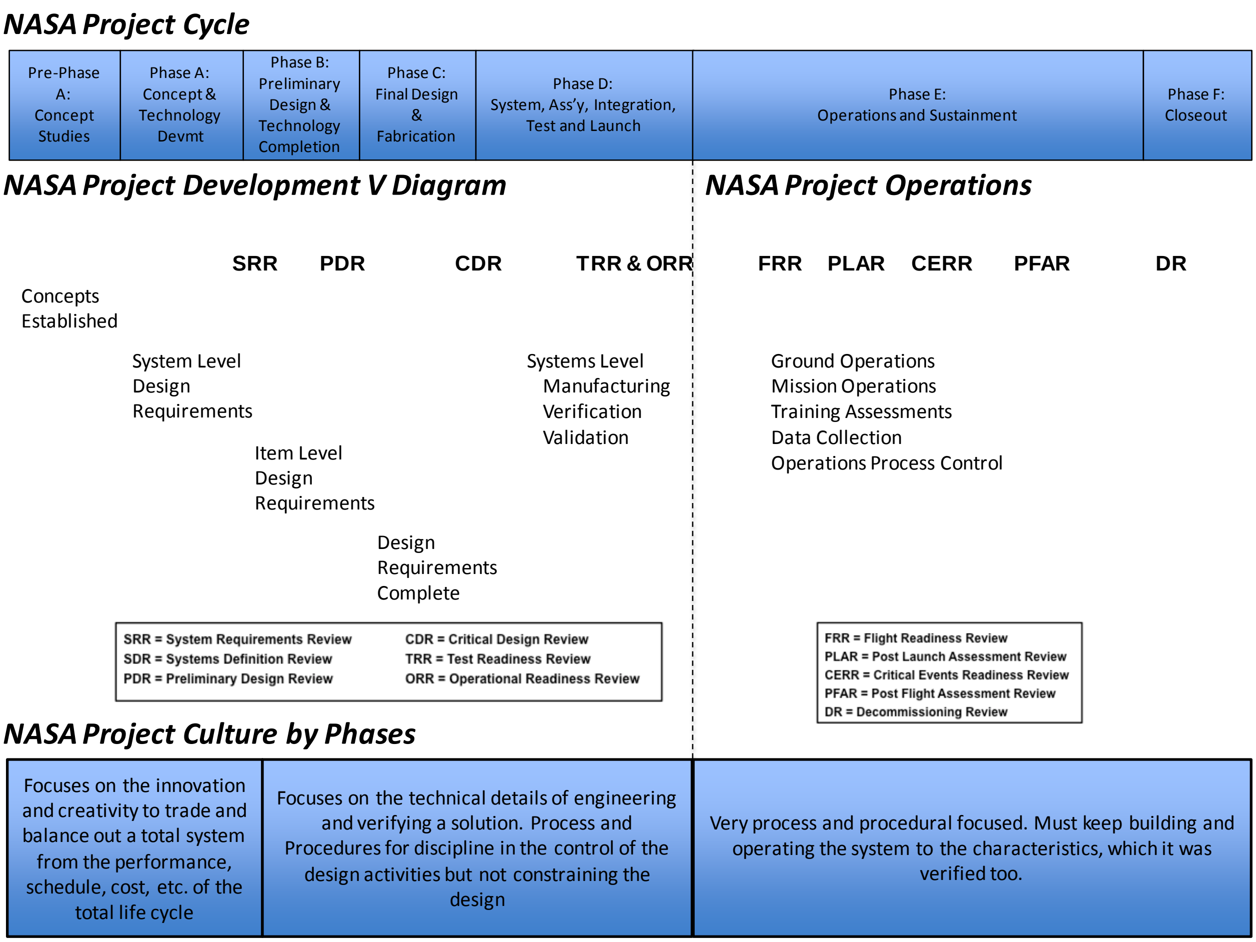


Figure 13. Lifecycle Characteristics with General Culture Attributes
[NASA Project Handbook, 2008]

11. Configuration Management

Configuration management during life cycle is another important task. Ares I SRM Thrust Oscillation is a good example of the function: The thrust oscillation problem was discovered prior to PDR but not in time to find a solution and impact the configuration. The Project decided to complete the PDR using a frozen configuration without consideration of thrust oscillation and when the solution matured have a delta PDR of the design impacts to the PDR configuration. Project Integration not only managed the initial PDR, but also managed the development of the solution and its impacts through trade studies using uncertainties, sensitivities, margins, constraints and system impacts, followed by managing the delta PDR.

12. Project Review Content

The reviews that occur at each major event of the lifecycle must be total systems reviews and include not only the documentation but have a major emphasis on the technical understanding and merits of the system as well as all the programmatic concerns of cost, schedule etc. The implication of the reviews is “understanding, understanding, understanding” and “communications, communications, communications”. Remember it is a System we are designing, building, verifying and operating. There has been some confusion and loss of purpose for these reviews as a result of findings from the Columbia Accident Investigation Board Report where NASA was criticized for “Power Point engineering” many of our critical issues with the Shuttle system. While this may be a valid finding, it does not negate the need for use of good presentations to develop and demonstrate the level of understanding of the integrated design details and to establish a framework to facilitate communications during these reviews. Over the last several years for many project reviews the process was focused on producing a collection of documents for review that were the subjective evidence of the design process but not on having good guided discussions of the integrated design issues. Another complaint is that the time required to develop these presentations takes away from the engineers doing "design work". While producing the presentations does take time, it is value added to the process because it forces a discipline on the presenter to communicate effectively and on the reviewers to understand and challenge the design.

C. Technical Integration Process

1. Process Model

As part of a team at Marshall Space Flight Center we have developed a model for Technical Integration. The following is a short summary of the model which is discussed in detail in NASA TP-2001-210992 [Blair, Ryan, Schutzenhofer, and Humphries, 2001]. This reference is for a launch vehicle design, but the principles and approach are generic and apply to any large system design.

The process starts with requirements and some concept of the vehicle. The concept is compartmentalized first by hardware subsystems or elements. The central part of the life cycle, i.e., from Architectural Generation to and including Detail Design is enabled by compartmentalization and reintegration, see Figure 14. While compartmentalization is necessary to accomplish the design of a large system, it does add complexity. Initially, the process starts with the launch vehicle definition and ends with the total integrated system design. Firstly, the system is compartmentalized into subsystems (hardware/software pieces). This creates interfaces that have to be tracked via interface requirement documents (IRD) and interface control documents (ICD). Each subsystem is then compartmentalized into design functions that design the system and subsystem so that the attributes of the each meet the derived requirements. To achieve the design, the design functions are compartmentalized into disciplines. The disciplines provide design results determined from analysis, test and simulations. We can define this decomposition and reintegration process globally in terms of the transportation system or in terms of each of its major elements such as the launch vehicle, verification system, operating system, manufacturing system etc. We will illustrate it in general using a launch vehicle; however, the process applies to the total system.

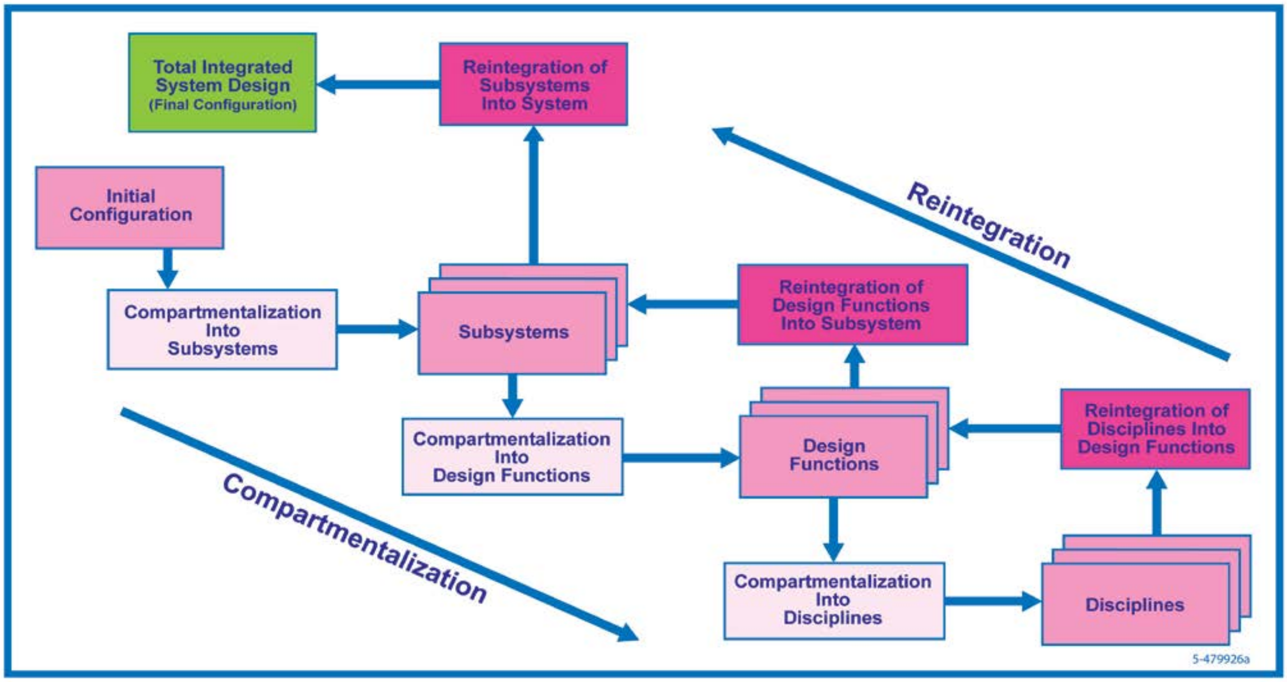


Figure 14. Compartmentalization and Reintegration

Thus the system is compartmentalized; now it must be reintegrated to obtain a totally integrated system design. Firstly, the disciplines are reintegrated. Adequate analyses, tests, and simulations are required to be accomplished. Then sensitivities, uncertainties, and margins need to be defined to provide information for risk assessment. Next the design functions are reintegrated. It must be assured that the attributes of the design meet the derived requirements. Furthermore, they are required to be verified. In addition, account of all interactions and nonlinearities has to be included. Finally, based on all knowledge of the design, a risk assessment is developed. This activity includes, at least, designers, disciplines, and S&MA. The final level of reintegration deals with subsystems and addresses interfaces. Specifically, the physical, functional, and informational flow across interfaces must be matched. Also interactions and nonlinearities related to the total system, in addition to those between subsystems, must be addressed. System integration and verification, operational constraints, and system risk are also considerations.

A total integrated system design is achieved when compartmentalization and reintegration are completed. Reintegration requires interactive communication by all members of the design activity where the compartmentalized subsystems (sub-subsystems, parts, etc.) are designed and then reintegrated into a balanced system design that can be verified and validated to operate at a specified risk level.

Further insights, i.e., "peeling the onion", into the design process can be gained in consideration of Figure 15. Shown here is an illustration of subsystems and design functions.

In the middle of the figure is an example of a system and some of its subsystems. For example, follow the solid blocks; they go from the launch vehicle system to the propellant conditioning system. Each is designed by the design functions indicated with the dashed arrows. At the upper left is the system set of design functions (planes) and at the top of the set is the launch vehicle system design function. It is responsible for all technical aspects of the system design. That includes technical integration, classical system engineering, hardware/software integration, etc. In addition, the system design function orchestrates and integrates the design activities. In a similar fashion the top plane for each subsystem performs a similar activity.

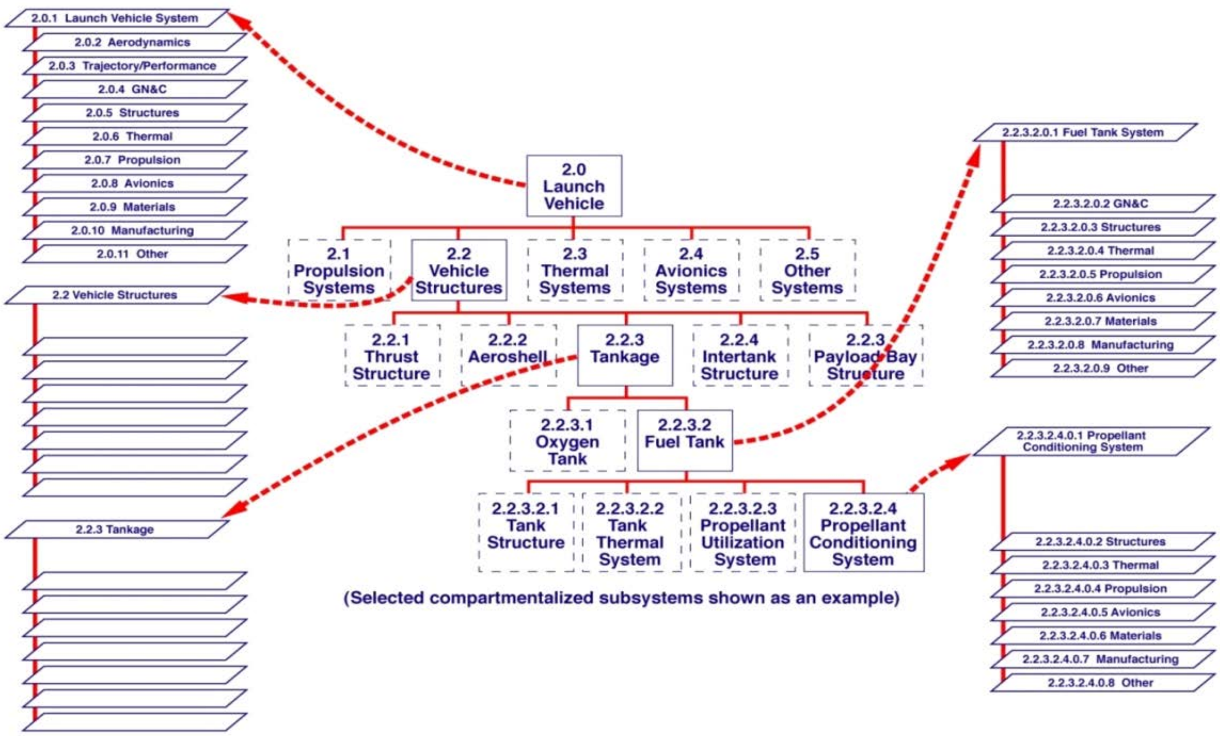


Figure 15. Typical Subsystems with Associated Design Functions

Integration of the system, design, and discipline functions is shown in Figure 16. The design functions are listed on the right of the figure. They provide the drawings, specifications and/or data books associated with each design function. For example, the aerodynamic design function provides the vehicle shape (outer mold line) and associated data books; trajectory/performance designs a balanced trajectory to achieve the target destination for the payload within all constraints, structures provides drawings and manufacturing specifications and so on. However, the system design function (plane) is responsible for all technical aspects of the system design.

The vertical conduits labeled requirements, architecture, and philosophy indicate formal flow of the associated information and it is controlled by the system. The system design is achieved in an iterative fashion via the design functions. Initially, a small group composed of representatives from each design function evolve a conceptual design(s) after an number of iterations. As the design matures through the Design & Analysis Cycle (DAC) process, the number of participants increases as well as the supporting data base. However the basic idea shown in Figure 16 remains in place but on a larger scale. The yellow conduit represents informal integration between the design functions and this is a key factor in achieving a balanced design. In addition, there is also significant informal integration within each design function. As the design converges, reintegration takes place and the converged attributes (green conduit) of the design formally flow to the system plane where they are eventually put under configuration control. If a balanced convergence with adequate margin can't be achieved, more iterations may be required or some system level requirements may have to change.

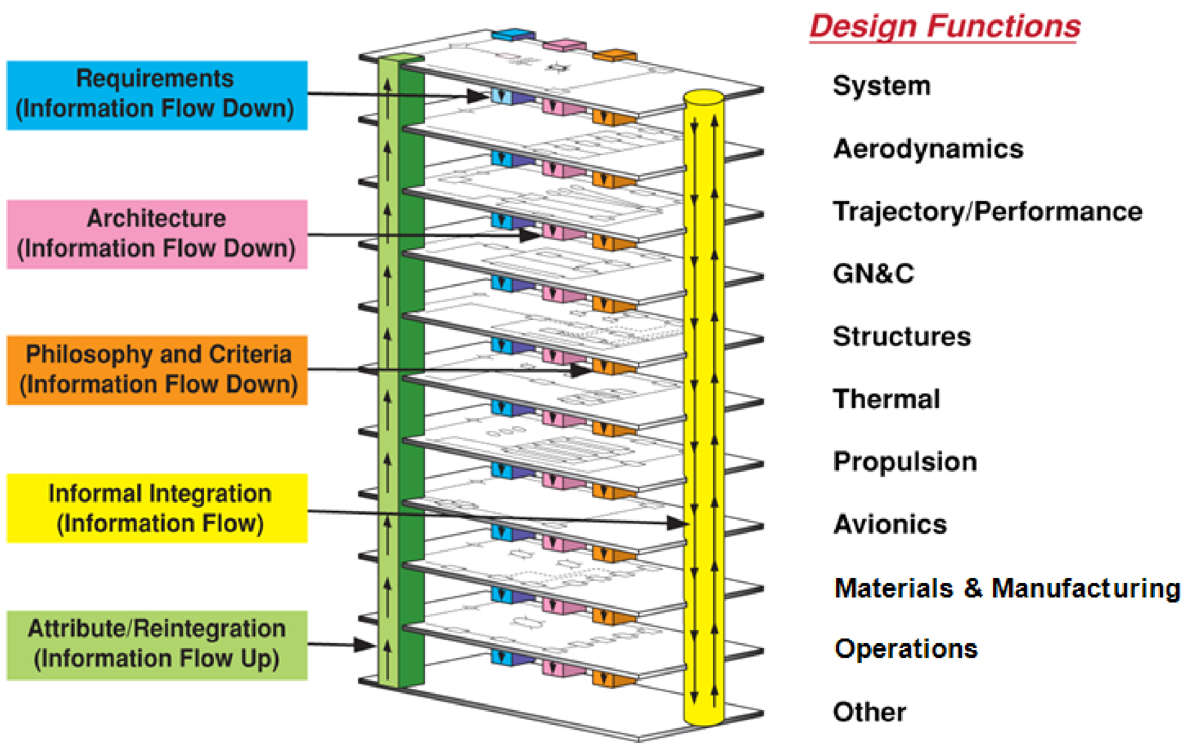


Figure 16. Technical Integration of System, Design, and Discipline Functions

We have discussed the stack of design functions that are required to design a system or subsystem. Now consider the process that takes place within a design function (i.e., what happens on the design function planes). This is where the design functions are compartmentalized into discipline functions. As an example, consider the Structures design function shown in Figure 17. The block titled "Design" represents the structural designer on the CAD machine, who is responsible for taking the requirements, architecture, and philosophy from the Systems plane and synthesizing a structure that meets those requirements. In accomplishing this, he/she is supported by a number of discipline functions, some of which are illustrated on the diagram. These include Natural Environments, Materials, Thermal, Control, Loads, and Stress. These discipline functions perform analysis, test, and simulation of the synthesized design, and provide the necessary databases. Discipline functions also are the keepers of standards for their respective technical areas.

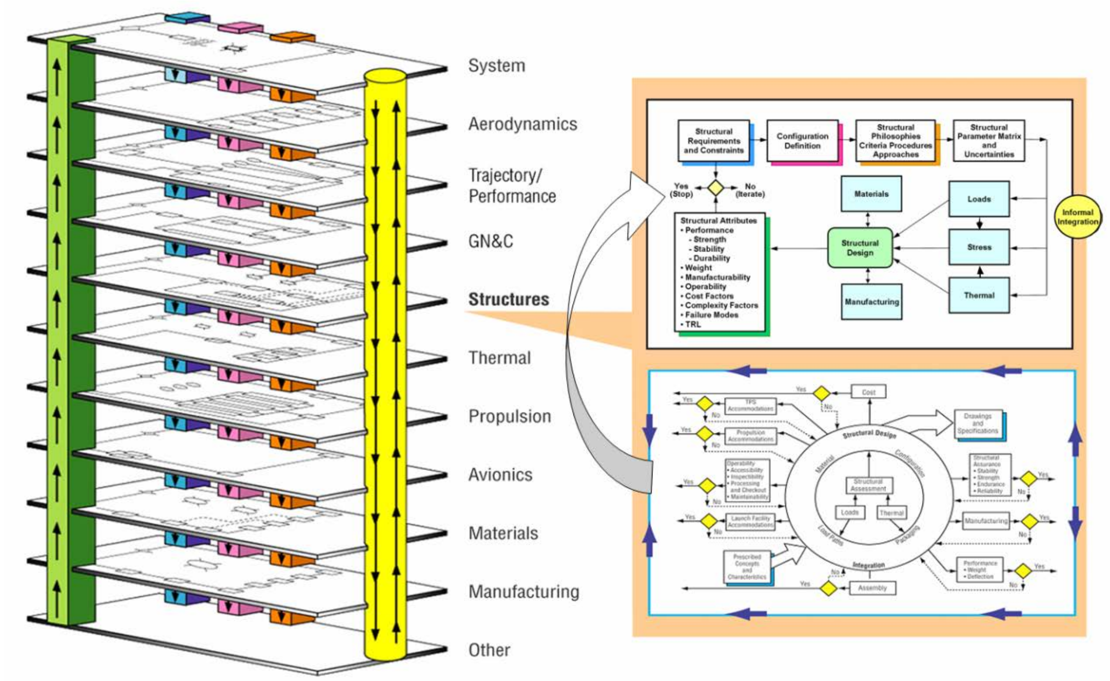


Figure 17. Structures Design Function with Discipline Functions and Decision Gates

The discipline functions provide the designer with information necessary to determine the structural design that will meet requirements. This is a very iterative process that requires extensive communication among the parties involved. Typically the designer hypothesizes a design (geometry, materials, etc.) from his/her experience and imagination, informed by interactions with the discipline functions. The hypothesized design is analyzed to determine its attributes, which are compared with the requirements.

The goal, of course, is to have the attributes match the requirements. This is shown diagrammatically as a single decision gate on the Structures design function plane. However, since there are multiple requirements to be met, there are multiple gates that must be successfully passed. Examples of these gates are shown on the diagram below the design function plane. They include attributes such as structural strength, endurance, and weight, accommodations of propulsion and thermal protection, and manufacturing and assembly compatibility. Along with these metrics the gates include cost and "-ilities" such as operability and other figures of merit required to assess the design. When the design has been iterated to the point that its attributes successfully pass all the gates, the Structures design function can feed the structural design and its attributes up to the System plane, where additional system attributes and interactions are assessed. With the completion of this assessment the drawings and specifications are output.

This process obviously does not occur in one pass, but requires many iterations and tradeoffs. Design inherently is a balancing and tradeoff process. To arrive at an acceptable design, there are multiple tradeoffs and iterations among the discipline functions and the design functions. We will not achieve a successful design unless there is intensive interaction and communication among all the participants. Iterations may also be required with the System plane, particularly if requirements relief or reallocation is required.

An area of design process improvement that is needed is integrated system analysis where we would better unify the subsystems, design functions, and discipline functions that are currently compartmentalized (simplify the compartmentalization process).

Designing for and managing interfaces is one of the keys to successful space products. There is a truism that says “Get the interfaces right and everything else will fall into place.” So the process starts with requirements that are derived to minimize the number and complexity of the interfaces and their functions. (See more detailed discussion in Section IVC3). As the compartmentalization process creates the need to manage interfaces between the subsystems, elements etc., the same is true for the information (includes data, assumptions, etc.) flow among subsystems and among the design functions and discipline functions. Input/Output matrices are useful tools to help manage this information flow. See Figure 18.

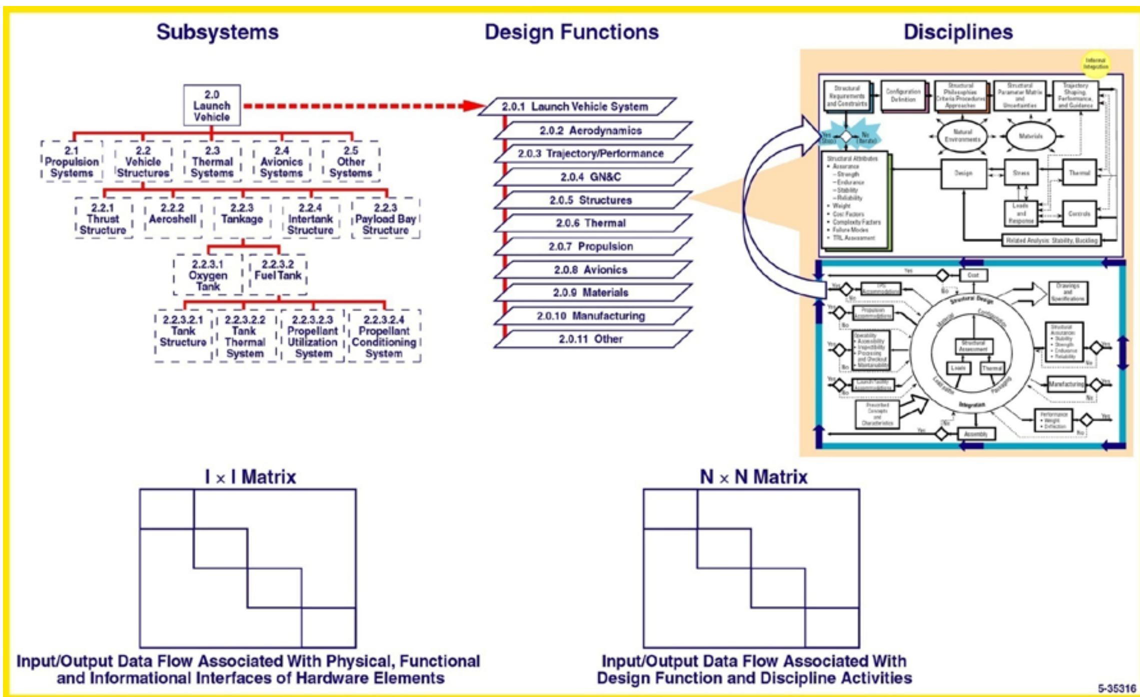


Figure 18. Matrices of Input/Output Information Flow

The IxI matrix. (Figure 19) is used for interface information flow among the subsystems and system, which are represented along the diagonal. Inputs to an element are on its vertical column and outputs are on its horizontal row. There are two types of information flow between the each pair of elements: requirements and approach to meeting the requirements. The first element provides its interface requirements to the second element, then the second element feeds back information on how those requirements are being met. This results in a clockwise flow of data. The matrix is a very handy tool to identify requirements, functions, and design characteristics before one spends the time of writing IRDs and ICDs. Later sections will provide more details on interface management.

Interfaces- I x I Matrix for Launch Vehicle

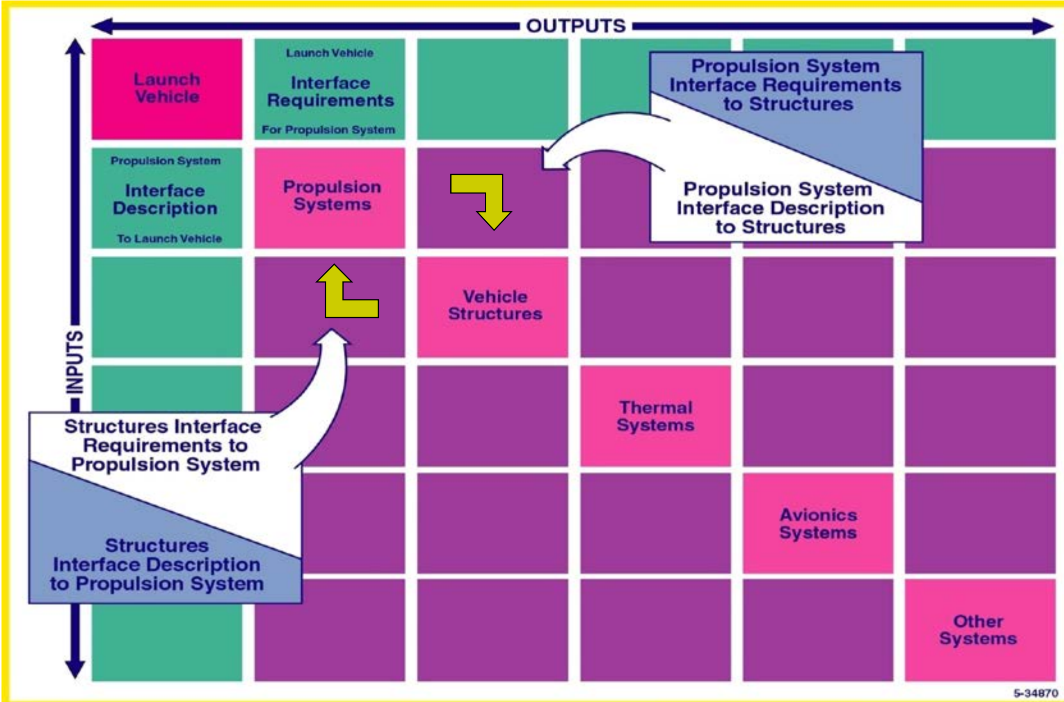


Figure 19. Interface Management Using the IxI Matrix

The same type device, called a data NxN, is used for information flow among design functions and discipline functions. This is a very powerful tool that helps keep track of the data and the meeting of requirements, as well as where each comes from and goes to. (Figure 20)

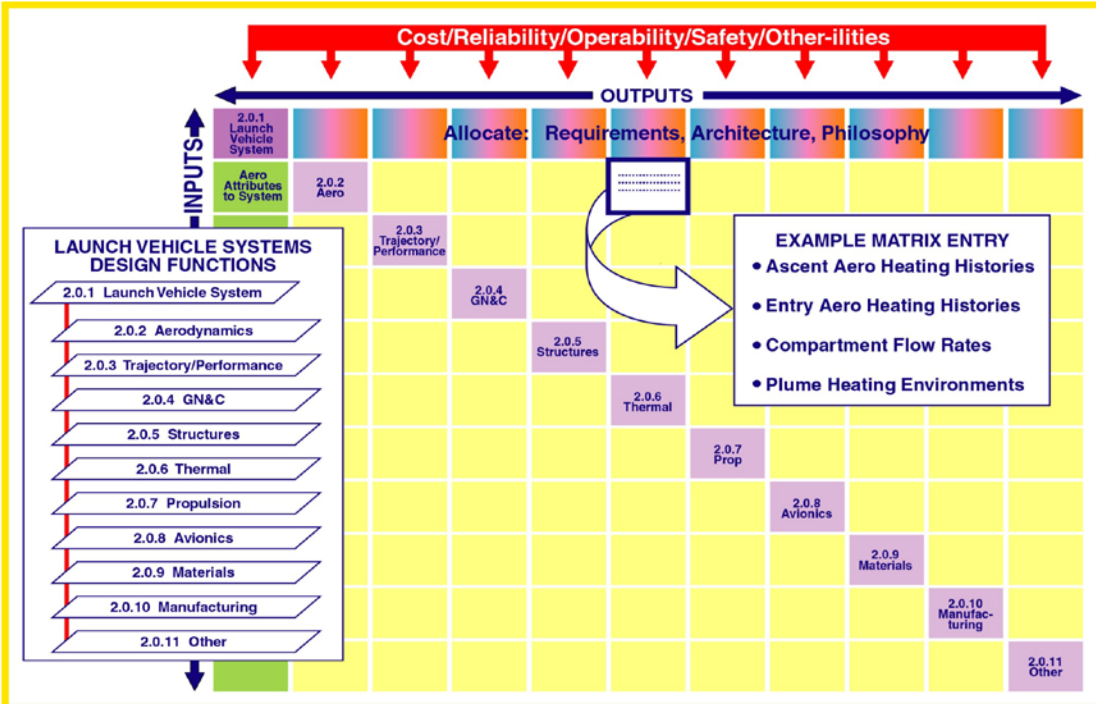


Figure 20. Information Flow NxN Matrix

The other main concern is the *interactions* created by the reintegration of all of the parts that were compartmentalized. Interactions can be stable or unstable, linear or nonlinear and can be very destructive in nature. Some of the interactions are well understood and have clearly defined practices for elimination or making them safe. Some of the known interactions are:

- Pogo
- Aeroelasticity/flutter
- Rotor machinery whirl
- Structure/control interaction
- Propellant sloshing
- Dynamic tuning
- Forced vibration
- Avionics/thermal interaction
- EMI/EMC

Many interactions are very difficult to predict and some may be unknown. The solutions to eliminate or control each interaction will impact the system. As stated previously, 80% of the problems experienced in aerospace engineering are due to a breakdown in systems engineering/technical integration, with most being lack of understanding of <u>interactions</u>. It is mandatory that all interactions be understood, designed for and managed.

There are other essential activities that are fundamental to the Technical Integration design process: Safety and Mission Assurance (S&MA) and Classical Systems Engineering.

Safety and Mission Assurance activities are an inherent part of the design activities. S&MA has three main components: (1) System Safety deals with hazard identification, detection, and mitigation; (2) Reliability identifies failure modes and causes, along with their associated probabilities. (3) Quality addresses process control and verification of the as-built hardware and software.

As stated previously, Classical Systems Engineering provides the framework, process control, and documentation of the Technical Integration process. It can be represented by the classical Systems Engineering "Vee" that follows the design life cycle.

Overall Technical Execution of the Design entails the integration of SM&A and Classical Systems Engineering into the Technical Integration process described above, as represented in Figure 21.

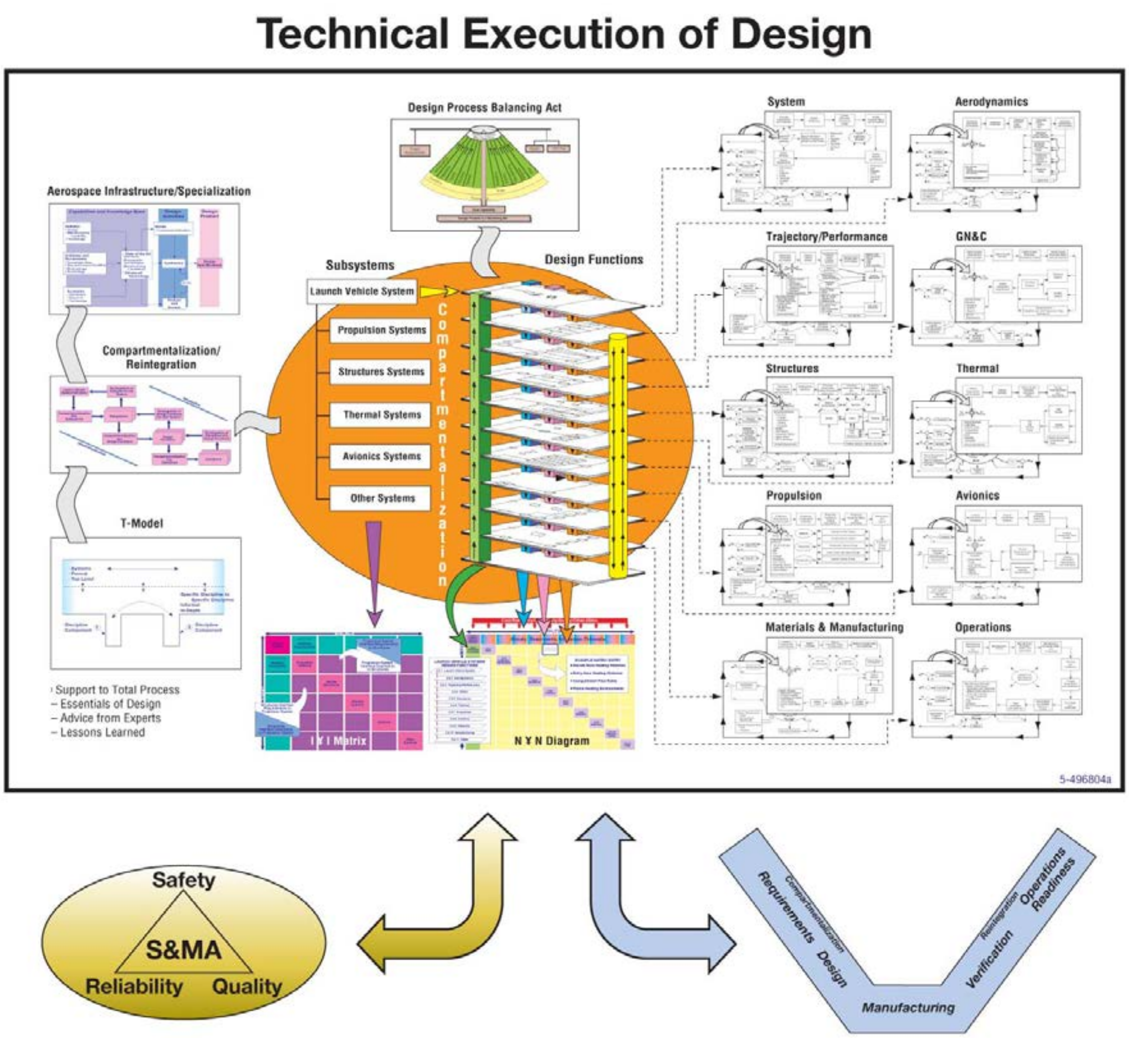


Figure 21. Technical Execution of Design

One great model for understanding technical integration is the “T-Model”. The T-model is shown in Figure 22 and is so named because of the horizontal and vertical components. It is a global model that focuses key features of technical integration. It delineates the system (horizontal) along with subsystems, design functions, or disciplines (vertical) while emphasizing the importance of formal and informal integration.

The horizontal portion of the “T” represents the System. The upper level (above the dashed line) of technical integration has been known by interchangeable names as formal integration, system integration, or top level integration. The leader and his or her office are the primary facilitators or operatives at this level of integration. The emphasis of this technical integration is primarily related to the systems aspects of the design process, i.e., technical management, certification of the system, etc. The primary focus is delivering the product with the proper balance of performance, cost, reliability, safety, operability, schedule, and TRL. Balance is achieved via managing and resolving conflict. All system related decisions and all system related technical conflicts are respectively made and resolved at this level. In addition, all system planning, control, and documentation is maintained at this level.

Technical integration below the dashed crossbar is informal and is a key enabler of achieving a successful design. It is given by interchangeable names of *subsystem, design function, or discipline* to *subsystem, design function, or discipline* integration (there are a number of combinations of these interactions), informal integration, or in-depth integration. The emphasis here is informal interactions (communication) between and among subsystems, design functions, or disciplines while including the system perspective. It can be hall-talk, phone calls, inter-office discussion, technical interchange meetings, etc. or other forms of communications. Since there are many vertical legs that affect each other, informal interactions among these elements are critical. The functional organizations are the primary operatives of integration for discipline-to-discipline aspects of the design process, while the engineering design functions are the primary facilitators of integration for the subsystem-to-subsystem specific aspects of the design process. The vertical legs of the “T” represent activities (designs, analyses, tests, simulations, etc.) associated with subsystems, design functions, or disciplines. They signify in-depth knowledge (in the vertical direction) but with a system perspective. This in-depth knowledge is required to be accurate and with the associated uncertainty defined.

A classical example of the T-Model is the game of basketball, which is both a team sport and an individual emphasis sport. The vertical legs are the fundamentals of the game such as passing, shooting, dribbling, footwork, hand and finger position on the ball, screening, blocking etc. For example, basketball is played with the ball being controlled with the fingertips, not the cup of the hands. Footwork is first played on the ball of the feet and movement is by shifting without crossing the legs except in special situations. In guarding an individual you in general don’t slap down on the dribbler but slap up or to the side otherwise you get called for a foul. The systems part is both formal and informal. The formal takes place by the team running patterns and then informal is taking advantage of what the defense does such as the back door, or the pick and roll. There are many formal plays also such as jump ball and out of bounds situation etc.

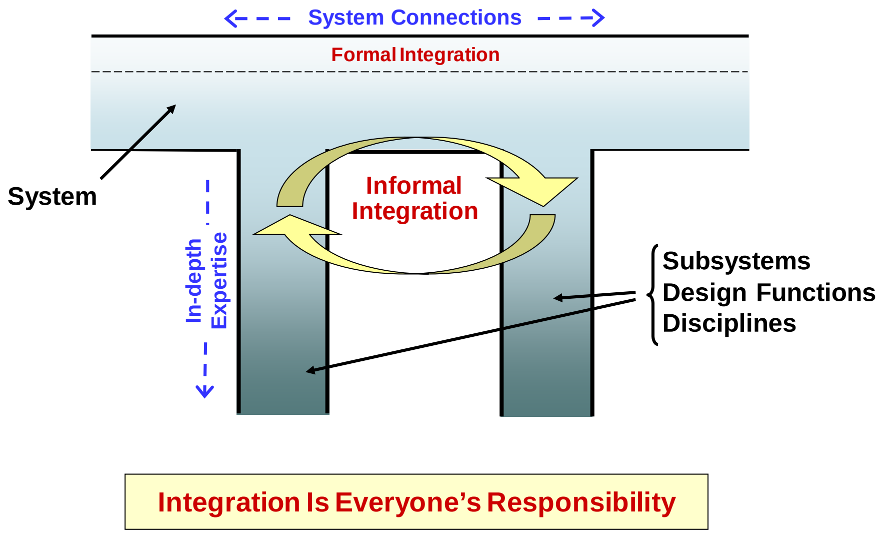
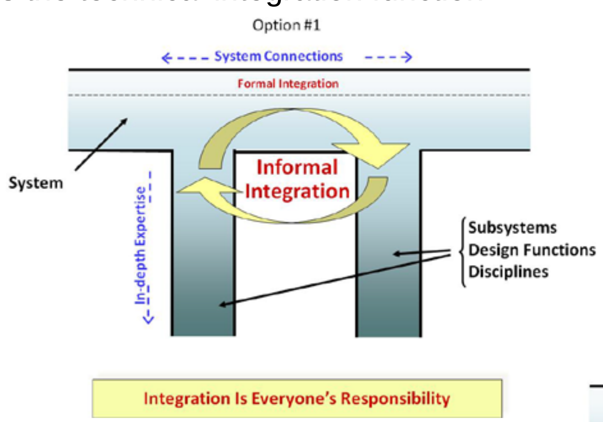


Figure 22. Classical T-Model for Technical Integration

The basic functions and characteristics of the T-Model for technical integration were discussed above. Depending on the approach used**,** the functions of the formal and informal aspects shift dramatically. Figure 23 illustrates two approaches to how much emphasis is given to formal integration. A highly formal technical integration approach greatly reduces the functional role of the informal integration. In our opinion moving in this direction greatly impedes the technical integration function.



*The Ideal is to only have enough formal control to insure order in the system but not so much that the human creativity and innovation is stifled thus option 1 is the preferred, while option two appears to be the tendency of today's culture.

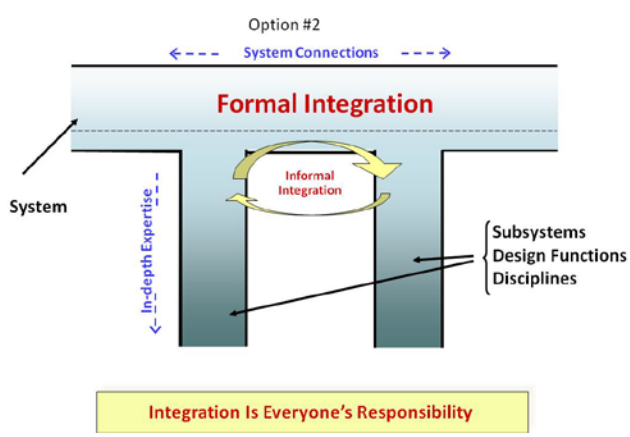


Figure 23. T- Model Technical Integration Options

The bottom line for managing integration is communications, communications, communications.

2. Examples of Historical Technical Integration Issues

This section will discuss two problems experienced in space exploration as illustrations of the complexity of integration. Discussed are:

Skylab Solar Array System Venting Failure
Space Shuttle Aerodynamics Anomaly

Skylab Solar Array System Venting Failure

There have been at least three similar venting incidents in the history of space flight. Two resulted in the loss of the vehicles and one crippled the payload. Those lost were the Atlas-Able-Pioneer (1959) and the Atlas-Centaur (1966). The one crippled was the Saturn Skylab (1973). The similarity in these incidents was that each had a shroud that came off during the transonic flight regime. In the first two incidences, the understanding of the flow physics was not known. Had it been known, the shrouds would have been designed so that they would have been under crush loads; however that was not the case. They were unknowingly designed so that during transonic flight the shroud load was a burst load that resulted in failure. These failures could have been prevented had the shrouds been adequately vented.

In the case of the Saturn Skylab an auxiliary tunnel was not adequately vented. The venting analysis was predicated on the assumption that the tunnel would be completely sealed at the aft end, but the aft end as manufactured was not sealed. The openings in the aft end were a result of lack of “technical integration.” The fact is this critical sealing requirement had not been communicated between aerodynamics, structural design, and manufacturing personnel, see [Lundin, 1973]. Furthermore, “system engineering” was not adequate. There was no dedicated systems engineer and that resulted in lack of effective integration.

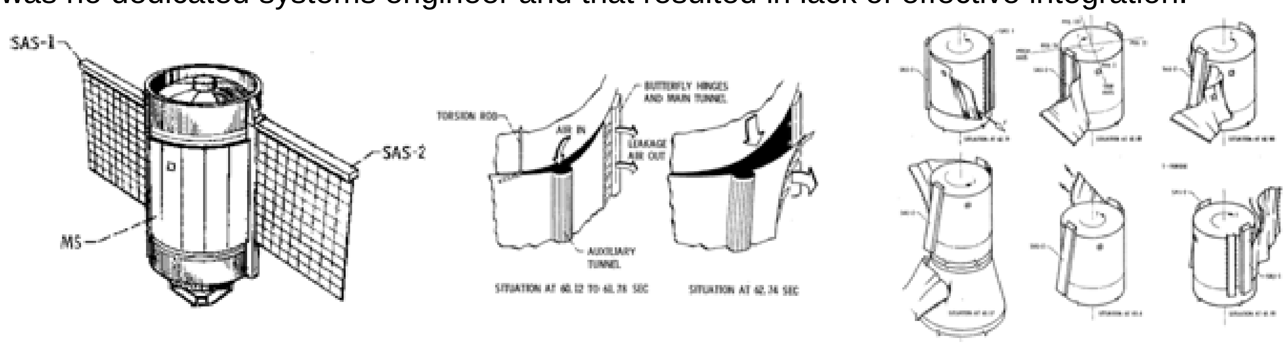


Figure 24. Saturn Skylab Solar Array System (SAS)

Shown in Figure 24 is the Skylab SAS. The first figure shows the system as it should have been deployed. In the middle figure, the destructive liftoff of the auxiliary tunnel as a result of the transonic flow induced burst load can be seen. The figure on the right shows the unwrapping of the micrometeoroid shield that was also a thermal shield. While the vehicle was not lost, the payload was crippled. However, eventually, a sun shield was added for thermal protection and the mission was saved. Saving the Skylab was a complex process that required two mission EVA activities [Belew, 1997].

This in-flight anomaly was a result of failures in both technical integration and systems engineering. All the requirements were not communicated. In reference, [Augustine, 1983], there are fifty-two laws (Augustine's Laws). The forty-fifth law states, "One should expect that the expected can be prevented, but the unexpected should have been expected."

Space Shuttle Aerodynamics Anomaly

The first launch of Space Shuttle (STS-1, Figure 25) produced several surprises. The first was the liftoff SRM propulsion induced overpressure problem which yielded the RCS system attachment arms and produced large dynamic oscillations of the vehicle. These phenomena will not be discussed. The second surprise occurred during ascent when two anomalies occurred. First the vehicle lofted significantly more than was predicted indicating that there was an unpredicted bias moment acting on the vehicle. The vehicle at SRB separation was approximately 10,000 feet higher than predicted. The second anomaly had to do with the orbiter wing loads. The trajectory had been designed to fly the vehicle conservatively at a predicted 65% of the design limit load; however, the strain gauges showed that the wing was experiencing 100% of the design limit load in some areas. The two effects were due to the same cause. In designing the vehicle, wind tunnel tests were required to develop the vehicle's aerodynamic characteristics. In order to accomplish an adequate test, the propulsion system plumes, including the atmospheric effect on their shape, had to be simulated using a solid plume simulator. Analytical techniques available to make the estimate of plume characteristics at that time were crude and thus gave an inaccurate answer. The plumes, in conjunction with the tunneling effect between the Orbiter wings and the External Tank and the Solid Rocket Motors, altered the aerodynamic distribution on the Orbiter wings, creating the unpredicted moment and the increased loads on the wings. Initially no one believed the strain gauge and aerodynamic pressure data, requiring that all the strain gauges be recalibrated. This recalibration showed that the strain gauges on the flight were accurate. Many thought that the pressure gauges were recessed too deep causing them to give inaccurate data; however after working the problem there was indeed a bias moment on the vehicle from the aerodynamic characteristics.

Figure 25. Launch of STS-1

The solution to the problem was complex. If the orbiter wing was beefed up to handle the increased loads there would be a 5,000 pound payload loss and a schedule slip of the next launch by 2 years. An alternate fix involved flying the vehicle at a -6 degrees angle of attack instead of the original -2 degrees, also at a payload penalty of 5,000 pounds. In addition the leading edge of the orbiter wing had minor structural beef-up and the External Tank protuberances had to be requalified to the new loads. Even with these fixes the original total structural capability was not gained, requiring that a Day of Launch I-Load Update approach be added to the operational procedures to bias the trajectory to a wind profile measured 4 hours prior to launch, increasing dramatically launch availability. Figure 26 shows the original Q-alpha envelope and the reduced envelope that resulted from flying the vehicle in the new way.

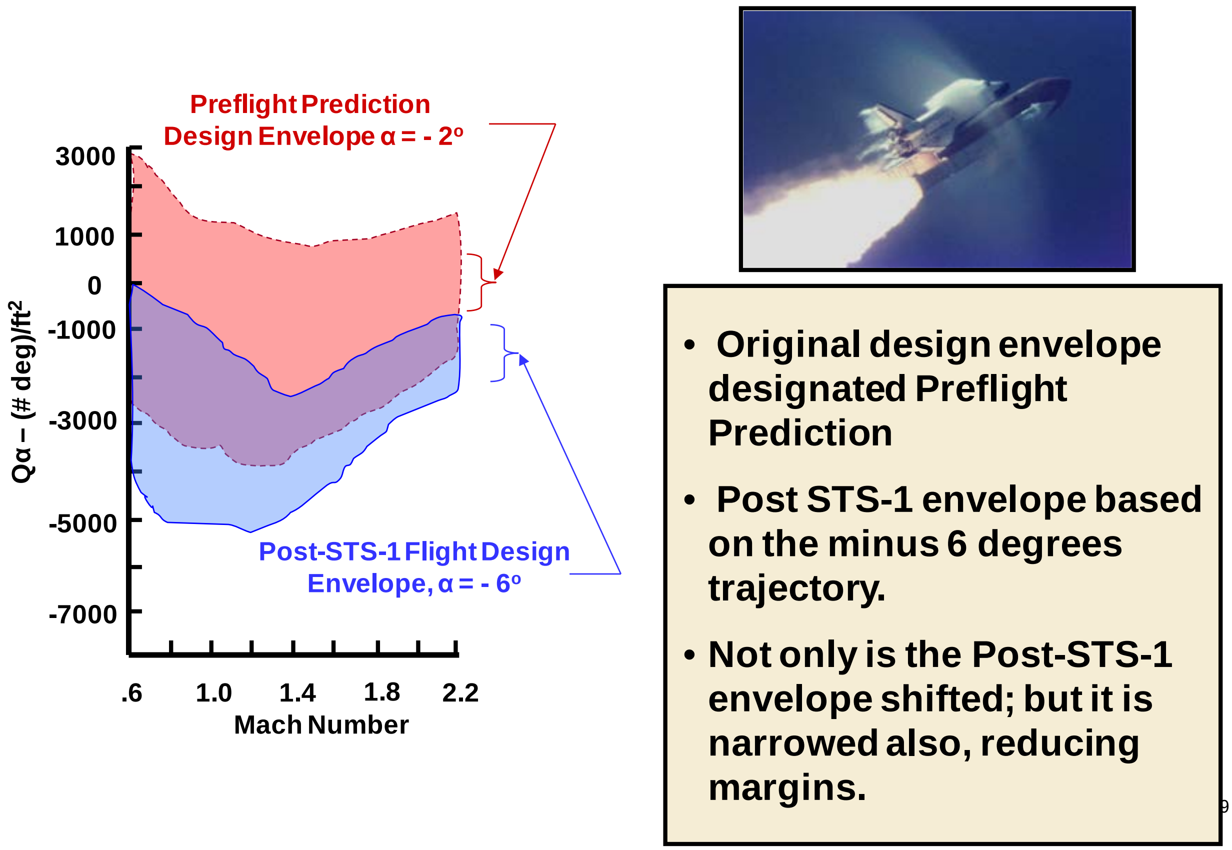


Figure 26. Space Shuttle STS-1 Aerodynamic Anomaly
[Ryan, 1996]

We have discussed the fundamentals of technical integration and two historical space system problems as examples of interactions that required unprecedented solutions for the projects to continue. In the next section we will go beyond the previous discussion and investigate the application of the process to understand Engineering the System with a glimpse of the diversity and complexity of the processes a project manager has to manage and make the critical decisions about the system.

IV. Expanding the Process of Engineering the System

We now want to go into more depth of the process just described in order to provide a better scope of key items a project manager must manage. In general we will use a launch vehicle as the example; however, the process applies functionally to each element of the transportation system and the total integrated transportation system. The process also can be applied generally to other large systems. This section will discuss engineering the total system using the following categories:

A. Process Overview
B. Requirement Decomposition and Derived Requirements
C. Subsystem and System Design
D. Lifecycle Activities Following Detail Design
E. Decision Making
F. Managing the Design
G. The Role of Organizations
H. Process for Achieving Excellence

A. Process Overview

We want to first discuss the underlying philosophy and or approach for the expanded process of design. We will then follow it with a look at some of the details of this expanded process that is required to understand and manage a space project. The design of aerospace systems is an integrated system approach. It is not a Rube Goldberg approach where we just throw pieces together and somehow make it perform some unclear function. As represented on Figure 27 it is an integrated design approach.

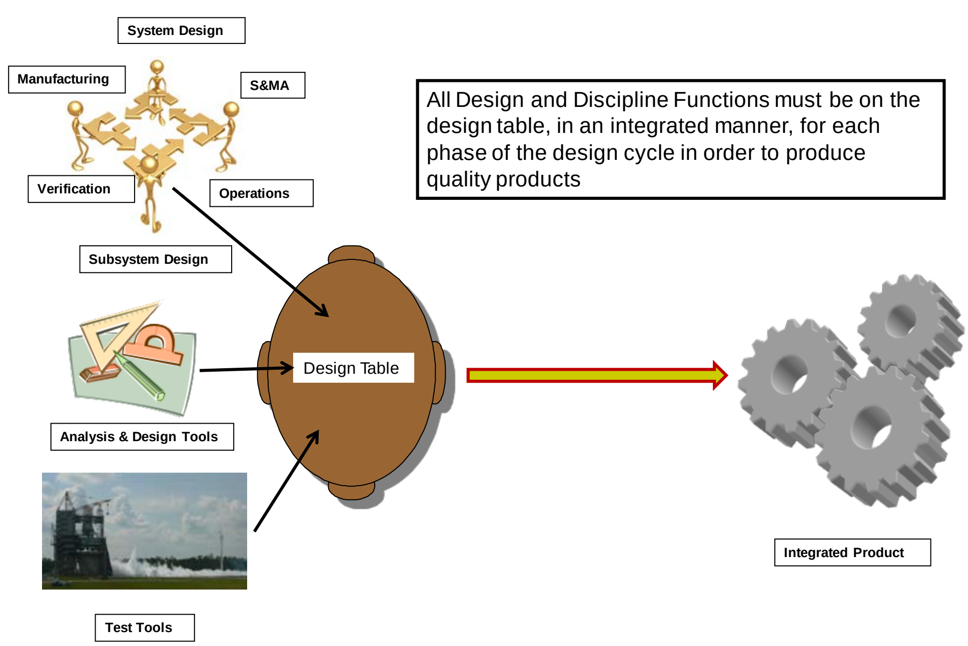


Figure 27. Lifecycle and Integrated Design Approach

As discussed previously, in the past we typically focused our design activities on the physical performance of the vehicle, then assessed the design for operability, reliability, and cost. What is needed is to design for the total life cycle, which means designing not only for performance, but also concurrently designing for the –ilities and cost. We describe this as "putting –ilities and costs on the design table". In order to do this, we need to have functional relationships that provide the designer with measures of costs, operability, reliability, manufacturability, etc., as a function of the design parameters so that the designer can choose a more balanced design. Obtaining the functional relationships needed for the above process is a challenge—only a few are currently available. Based on historical or other data, people in all technical areas should work to identify functional relationships that connect the –ilities and cost to design variables, thus working toward making the –ilities and cost concurrent "design-to" attributes along with performance.

Pugh in his book, "Total Design" [Pugh 1991] deals with this concept of integrated design using a cylinder built of integrated sections where information flows from one part to another and all the interactions are accounted for. (Figure 28) The model is highly iterative. It is life cycle centered, includes programmatic and technical disciplines and encompasses all the major activities. The outer shell is driven by the business and customer expectations and requirements. The inner core is the life cycle and the basic design. At each major element is a circle divided into activities in terms of the order of importance. The block arrows are design activities or functions including some of the programmatics. This excerpt is only one of many examples that he covers in the book with the emphasis as the title indicates on Total or Integrated Design.

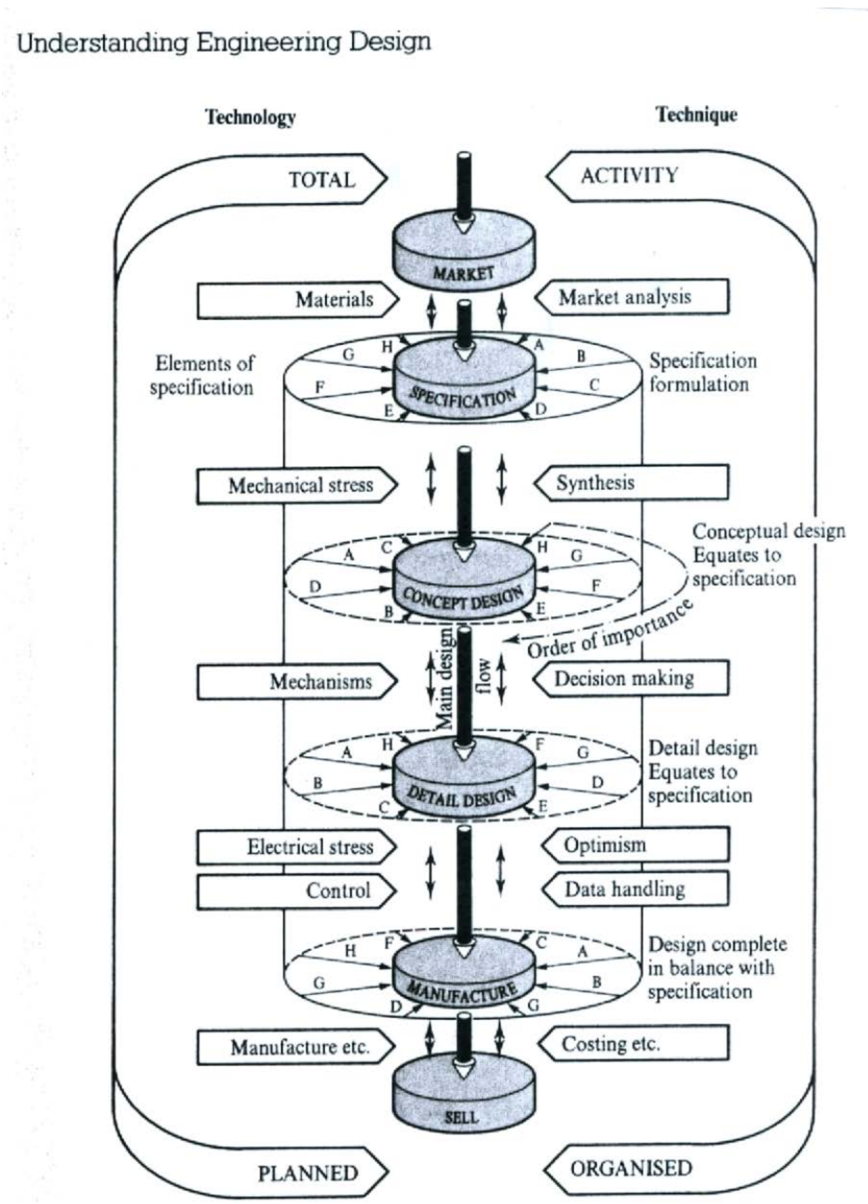


Figure 28. The Pugh Engineering Design Model
[Pugh, 1991]

This expanded process results in a system that is balanced in the best manner possible under the constraints and requirements of the project. Obviously these constraints are not only technical but are political, business etc. as well. Figure 29 is an example of some of the trades and balancing that are present in the design of a launch vehicle. The chart is taken from the Space Launch and Transportation Systems book [Larsen, et. al., 2005]

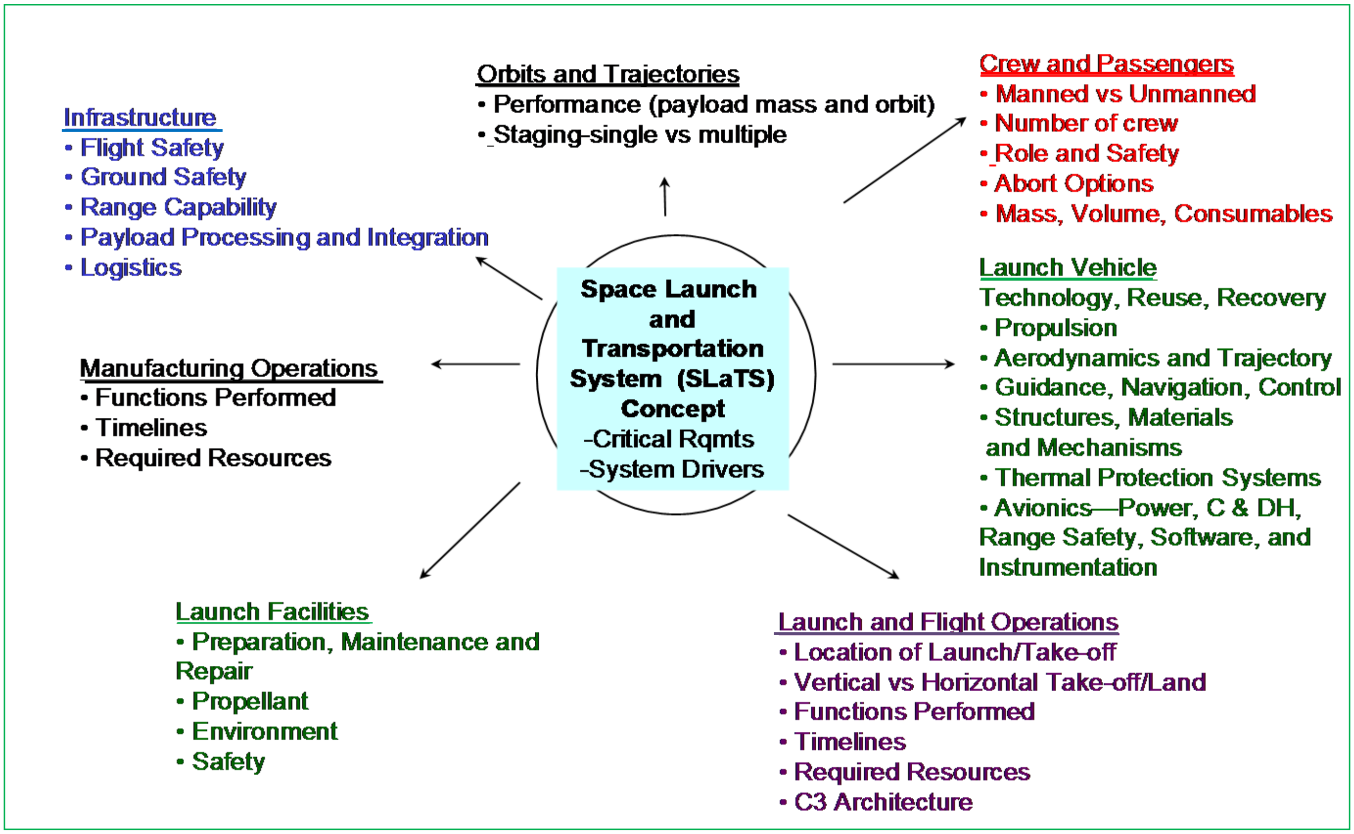


Figure 29. Example Trade Spaces Involved in the Design of a Launch Vehicle [Larson et.al., 2005]

The examples are not the total trade space but provide an illustration of the complexity introduced by the number of functions, subsystems, and processes that must be considered, traded and balanced. There are many subsets to the areas listed that are also a part of this trade space. How we trade and balance these functions, subsystems, elements, and components is clearly one factor in producing a successful product.

The expanded process begins with the mission and general requirements necessary for the mission. This set of mission objectives and initial requirements allow us to apply some general design understanding of what the system architecture might look like. With this starting point the first task is to determine what functions must be performed in order to achieve the objectives (Functional Analysis), followed by a list of all the ways that are possible for performing each function. Taking this voluminous set of potentials for each function, various combinations of these potentials are put together to form different potential architectures for the systems. These are evaluated and screened based on criteria that have been determined earlier, and the best approaches are selected. Notice that in the formulation of the lifecycle functions during both the architectural selection and the concept design and selection phases, all aspects of the lifecycle must be a fundamental part of the trade space. However, at these early phases of the lifecycle there is less detail in the functions than will exist in the later implementation phases. This means that the total system must be balanced during design, iterated some during verification, and occasionally fine-tuned during the operational phase. The culture is different during the formulation and design phases than the culture during the operational phase as was discussed earlier. Therefore architectures must consider the total system and for a launch system, include at least the vehicle, operations, manufacturing, verification, and infrastructure. The architecture must now be converted into more detailed set of concepts that potentially can satisfy the architecture and the objectives and requirements. This is accomplished with a sizing program based on historical characteristics of previous launch systems. A small set of the concepts are then carried through a more detailed concept design cycle and a final concept selected based on the before-mentioned criteria. Figure 30 is a top level look at the process flow.

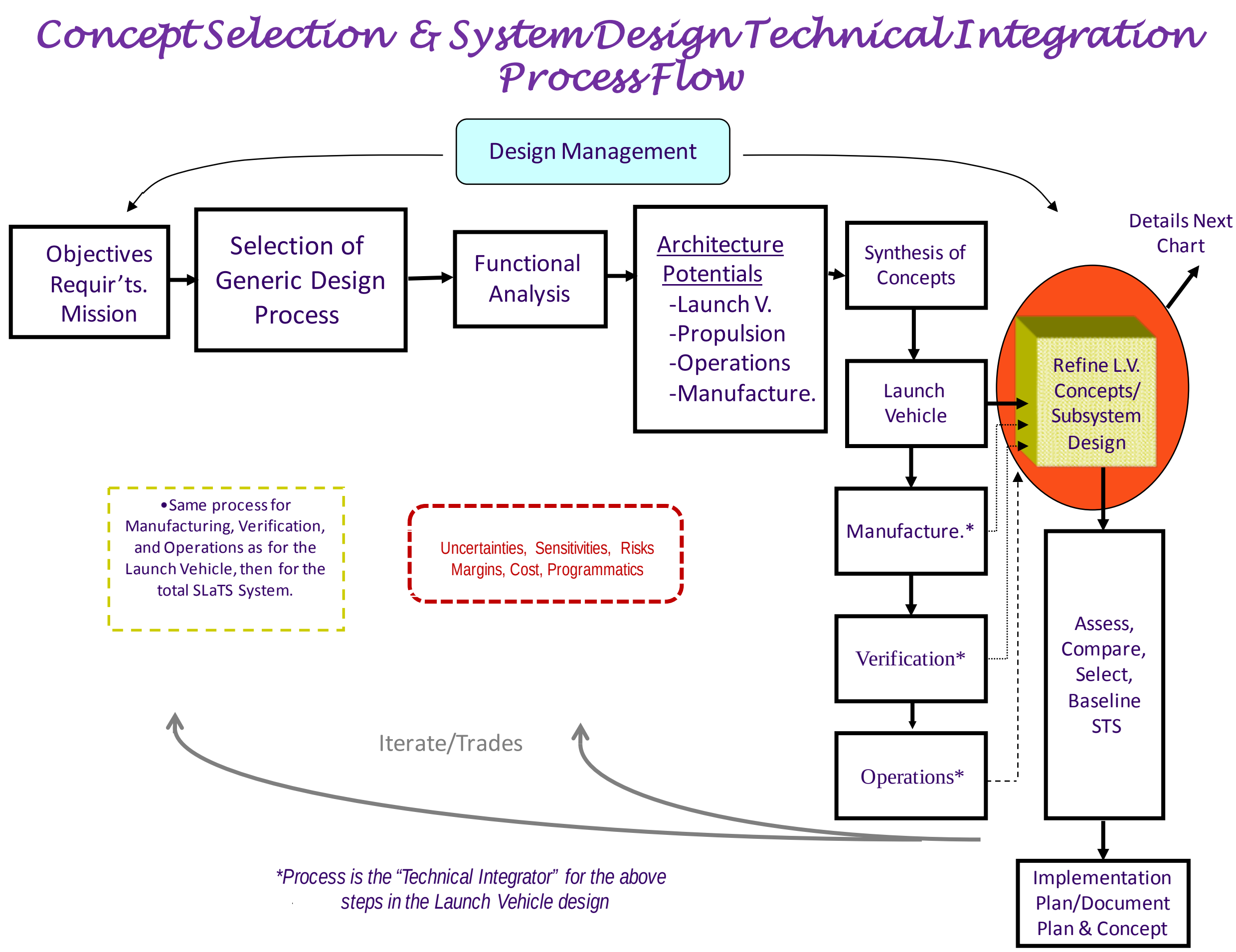


Figure 30. The Top Level Technical Integration Process for Selection of the Concept and the Design of a Space Launch and Transportation System

Figure 31 provides the basic design objectives of program or project. As this figure shows design must not only be concerned with performance but also must design the system to preclude failures during the lifecycle or have means of mitigating them. This means that during design at any stage of the lifecycle the potential failure modes must be identified and addressed. Using these objectives as the focus, the approach for refining the concept design and conducting detailed design of space launch and transportation system is shown on Figure 32, where the analysis and test portion is commonly called the Design Analysis Cycle (DAC).

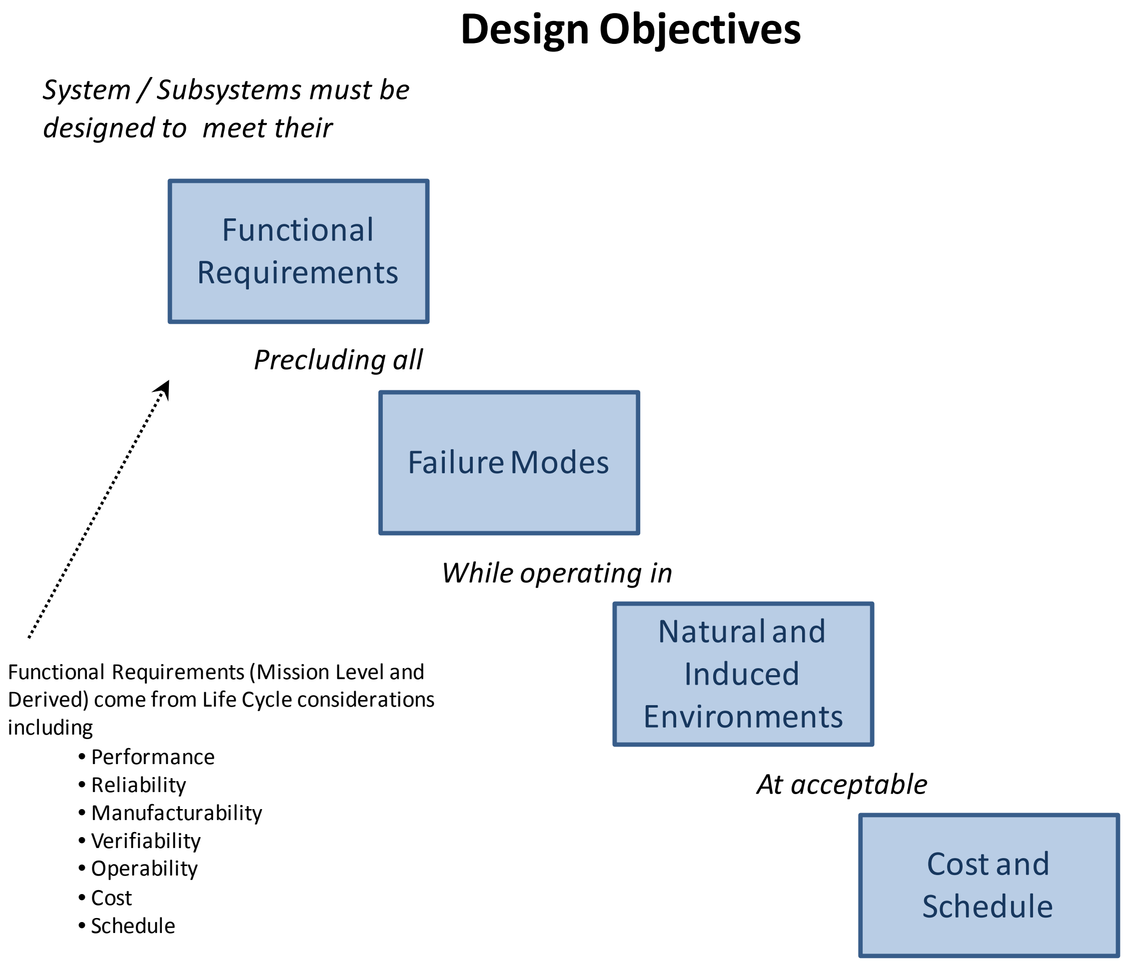


Figure 31. The Design Objectives of a Project or Program

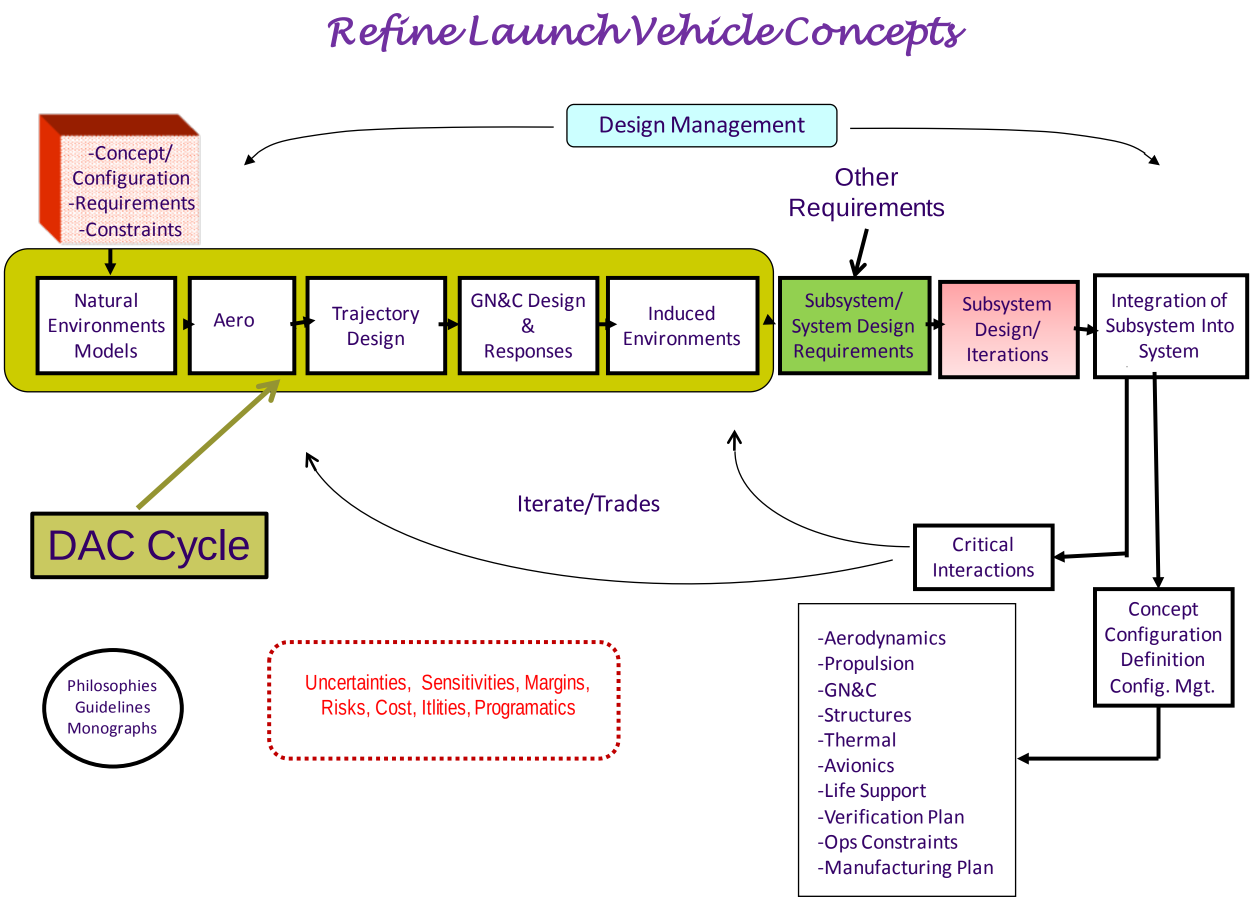


Figure 32. The Elements of a Space Launch and Transportation System Design Cycle

The program or project manager with support of the chief engineer and the engineering department, along with support of any other organizational elements required, are responsible for the management of this process. The process starts with the identification/characterization of the current concept or configuration and the basic requirements. Starting with this information the Design Analysis Cycle (DAC) begins by defining the natural environments models to be used in all analysis. Based on the initial configuration and mission profile the vehicle aerodynamic characteristics are defined for each mission key timeline. The trajectory is redefined using the updated information. The trajectories then become the baseline for generating all the rigid body responses and updating the GN&C system. Using the data from these various areas all the induced environments (Loads, Thermal, Vibration, etc.) are developed at a 3-sigma level. Combining all the information developed the system can now define the derived requirements which are added to the base requirements and then flowed down from the system. These requirements are now given to all the subsystems to update or accomplish the design of each subsystem. Each of the updated subsystems is integrated and the system balanced through an iterative process. When completed the new configuration with all its accompanying data and characteristics are baselined.

Figure 33 is an attempt to illustrate the design process in some more detail, but still in a simplified form. The difference between this flow and Figure 33 is the block illustrating all the plant (system/subsystem) models and analysis that includes GN&C, loads, thermal, vibration and other required analysis. Additional detail is shown for material and manufacturing characterization and the internal response/loads typically called stress, safety factors and margins added to account for unknowns. In the lower section are the design, manufacturing and verification, assembly and operations. Iteration loops are shown to illustrate the constant need to balance the total system.

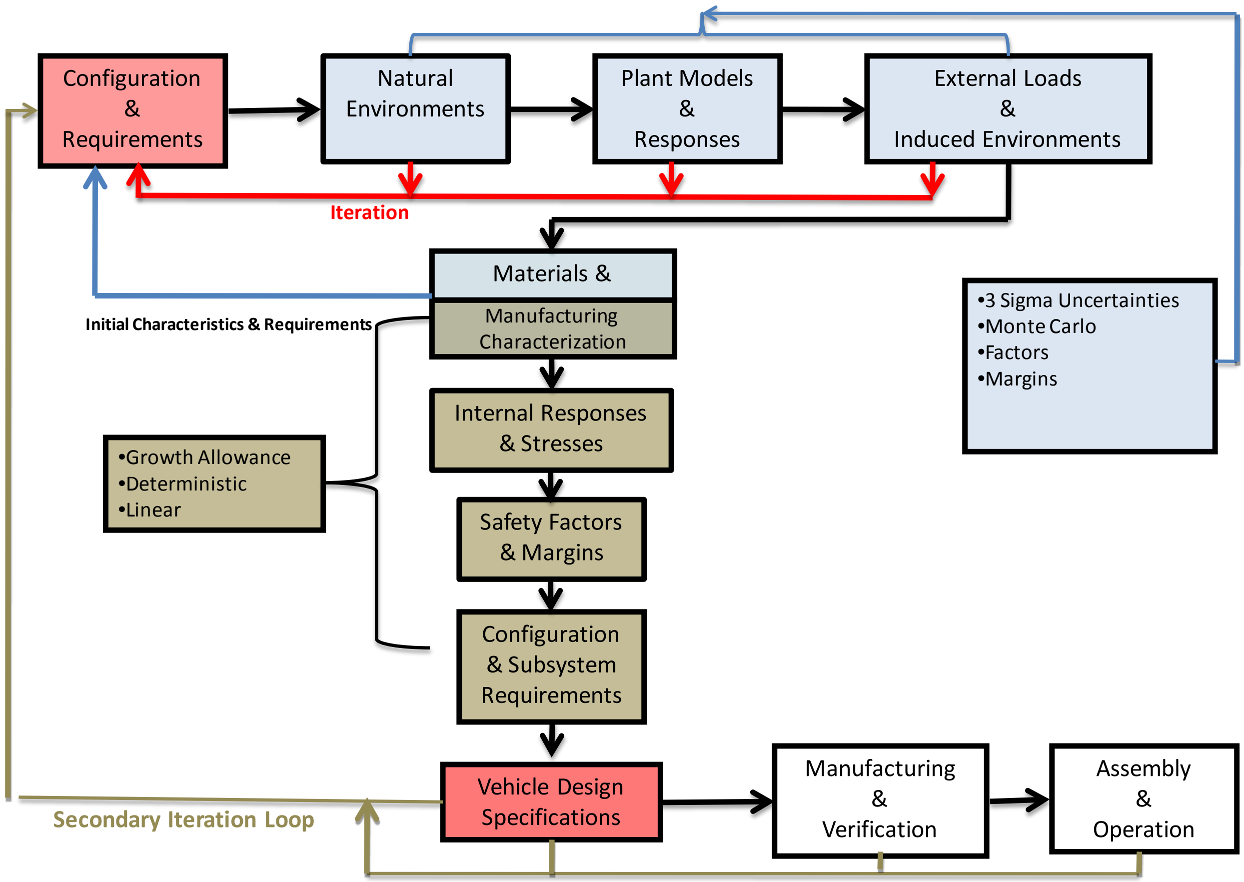


Figure 33. A Simplified Flow Diagram of the Design Process

The functions of the activities that lead to the design specifications are:

- Identifies all potential failure modes of the system and subsystems.
- Conducts the analysis, test, simulation, using uncertainties, sensitivities, interactions, margins, risks and trades to arrive at the derived requirements for the system and subsystem design that includes the launch vehicle, manufacturing, operations, -ilities etc.
- These requirements not only include the subsystem design requirements but also the best way to fly the vehicle in the best balanced state.
- Project managers are responsible for managing this effort in a way that makes the process efficient, and does not become overly conservative.

The functions of areas captured in the design, manufacturing and operational blocks and the reintegration of the system are:

- Using the derived requirements and how we fly the vehicle, the system and subsystem is designed, built, verified and operated.
- The system is balanced using trade studies based on uncertainties, sensitivities, risks and margins along with cost and schedule.
- Project managers are responsible for ensuring that the system is balanced, safe, reliable, and has adequate margins and flexibility.

B. Requirements Decomposition and Derived Requirements

The selected concept becomes the baseline for the design process which is started by decomposing the requirements into lower level requirements. This is a very iterative process and results in more and more in-depth lower level requirements typically called derived requirements.

The decomposition of requirements to lower level can become very intensive and detailed. For example, decomposing the requirement that the system have attitude control for path deviations and that it must be stable can take the following top-level form:

- Navigation system avionics
    - Sensors and sensor location
    - Thermal conditioning
    - Shock and vibration isolation
    - Software
- Flight computer
    - Software for control system algorithms
    - Processing cycle time implementation
- Thrust vector control system for attitude control forces that leads to requirements for
    - Gimbal throw angle
    - Gimbal rates
    - Gimbal accelerations
    - Gimbal system uncertainties
    - Response amplitude and phase as function of frequency
- Structural constraints
    - Stiffness/frequencies
    - Load paths/attachments
    - Slosh baffles
- Resulting manufacturing, verification and operation requirements

These top-level requirements are decomposed and expanded as the design process matures. As the subsystem’s design evolves, it must be reintegrated back into the system and the system effects determined. This can result in a change in its design or a change in the derived requirements including additional requirements.

Managing the development of the derived requirements is crucial to the success of the project. The derived requirements usually are many of the drivers to the system design and operations. Management of this activity is very detailed and time consuming, with the derivation of the derived requirements utilizing large manpower and computer resources. At least the following two areas are involved in the process.

- Natural Environments
- Induced Environments

1. Natural Environments

The natural environments are the environments which exist whether a space system is present or not. They are the environments that exist due to the natural state of our universe. They include atmospheric density, temperature, winds, solar pressure, magnetic fields, etc. A more detailed list is shown on Figure 34 for the terrestrial and space environments. Figure 35 shows examples of the atmospheric winds, temperatures, and density. These environments are a statistical measure over time at the various launch sites at different points in space. Each has to be modeled to be compatible to the mission event being analyzed. Ensuring this compatibility is one of the integration tasks the project manager and chief engineer must perform.

- Terrestrial Environments:
  - Winds, Turbulence
  - UV & IR Radiation
  - Flora & Fauna
  - Atmospheric Electricity
  - Sea States
  - Geological Hazards
  - Atmospheric Thermodynamic Properties
  - Precipitation, Fog and Icing
  - Cloud Characteristics & Cloud Cover
  - Tornadoes, Hurricanes & Severe Weather
  - Atmospheric Constituents
- Space Environments:
  - Near-Earth Thermal
  - Meteoroids
  - Orbital Debris
  - Magnetic Fields
  - Atmospheric Constituents (Atomic Oxygen)
  - Solar Activity & Atmospheric Density
  - Ionizing Radiation
  - Plasma/Spacecraft Charging

Figure 34. List of Typical Natural Environments Necessary to be Defined for Space Systems Design and Operations
[SLaTS Course - Natural Environments, 2010]

Natural Environment Examples

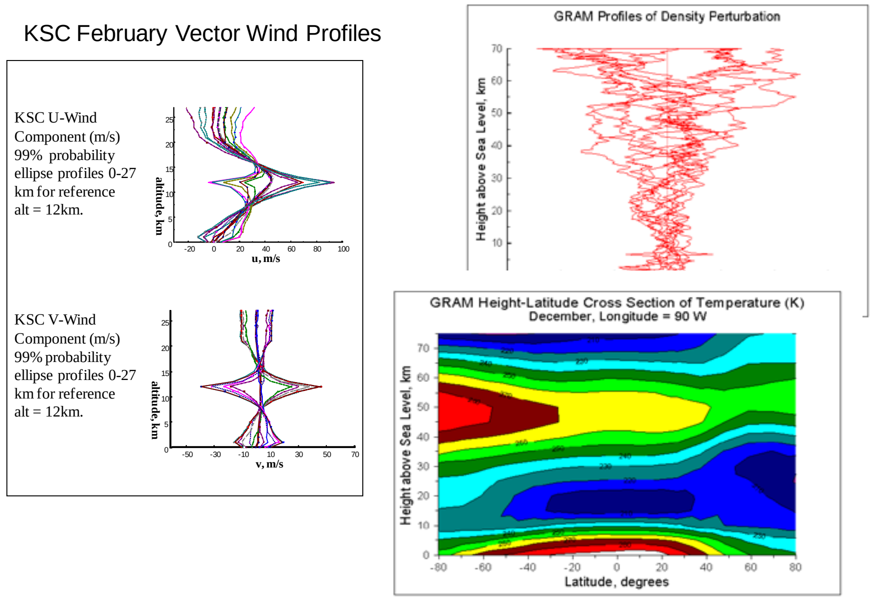


Figure 35. Atmospheric Winds, Density and Temperature Examples
[SLaTS Course - Natural Environments, 2010]

2. Induced Environments

Induced environments are environments caused by the launch vehicle, spacecraft or other elements and their operations, producing interactions within their own systems and with the natural environments. How well we manage the derivation of the induced environments and the resulting derived requirements have major impacts on the space system being designed. It is a very critical area for management to ensure adequacy without undue conservatism. The resulting induced environments that typically drive the derived requirements include: (Only those in italics will be discussed as examples)

1) Aerodynamics
2) *Trajectory responses*
3) *Control responses*
4) *Vehicle loads*
5) *Induced thermal environments*
6) Vibroacoustics
7) Electromagnetic interference
8) Radiated RF energy
9) Pyrotechnic shock
10) Vehicle-generated debris
11) Effluent from propulsion systems, separation motors, other systems
12) etc.

Trajectory Responses

Trajectory design integrates and balances the launch vehicle system between the various subsystems and design functions, determining the best path to fly to the target. It also determines whether the vehicle design supports the capability to reach the target and anchors flight operations. Designing an ascent trajectory is complex because of the changing environments, from atmosphere to exo-atmosphere, and the variety of optimizing parameters and constraints. To design a good ascent trajectory, we must include liftoff, pitch-over, flight through maximum dynamic pressure, staging conditions, and flight in the vacuum of outer space. Optimizing the trajectory requires that we understand and balance among the highly variable characteristics of each event of the trajectory. The atmosphere, vehicle motion, forces, and vehicle mass all vary rapidly as the ascent trajectory progresses. As a result, constraints such as clearing a launch tower, minimizing structural loads, and limiting acceleration affect different parts of the trajectory, as do abort requirements. The trajectory parameters are optimized in different ways over various flight phases. For example, the initial pitch-over angle and the vacuum flight path are optimized for maximum payload delivery, while the liftoff and flight through the region of high dynamic pressure are more constrained. The liftoff trajectory is constrained by tower clearance requirements. The predominant factor in the high dynamic pressure region is usually vehicle loads, which are a function of the dynamic pressure and the wind effects. We have many trades and optimization parameters available for designing the flight trajectory. We consider each event and then integrate the total trajectory, which means we must balance the system among the conflicting requirements of each. Figure 36 is a flow diagram of the trajectory design process showing many of the inputs and outputs of the process. The trade studies shown in the small box are key to achieving an adequate product. Examples of these trade studies are listed in the following paragraph.

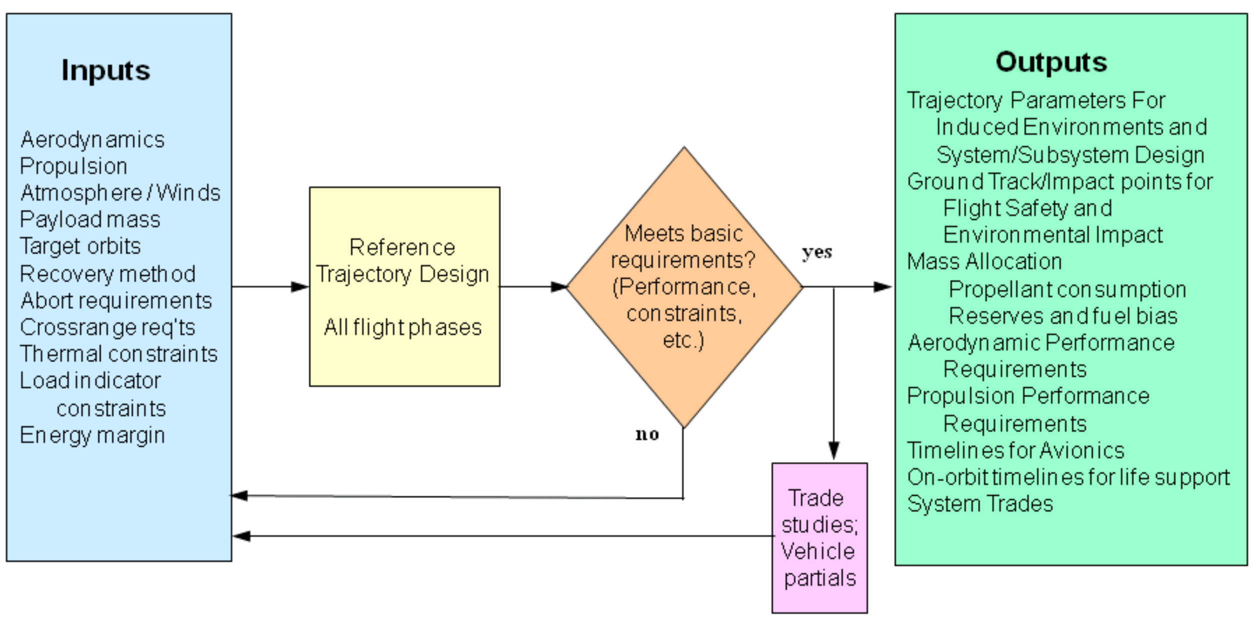


Figure 36. Typical Trajectory Design Inputs, Outputs and Trade Studies Flow
[SLaTS Course -Trajectories, 2010]

Trajectory Design Trade Space

- Wind biasing: Impacts structures, vehicle control, and launch availability.
- Aborts: Examination of abort trajectory possibilities and alternate landing sites. The abort trajectories can drive some aspects of vehicle design.
- Mission orbit: A different target orbit impacts the payload performance, the sizes of stages, and thermal/structural/etc. disciplines due to use of a different trajectory.
- Performance to final orbit: Mix of launch vehicle and upper stage, delta V split
- Vehicle partials: The impact on payload, vehicle constraints, and landing success from a change in each important trajectory design parameter
- Launch site choice: Trades on performance, launch window variation with launch site, stage impact areas
- Launch window analysis: Launch window payload penalty; how often does the launch window recur?
- Rendezvous: How many days between launch opportunities?

Figure 37 represents a typical launch vehicle trajectory for a vehicle with a flyback booster. Major events of the trajectory as pointed out on the figure include liftoff, optimized pitch over, maximum dynamic pressure, pitch/yaw optimization, staging, and orbit insertion.

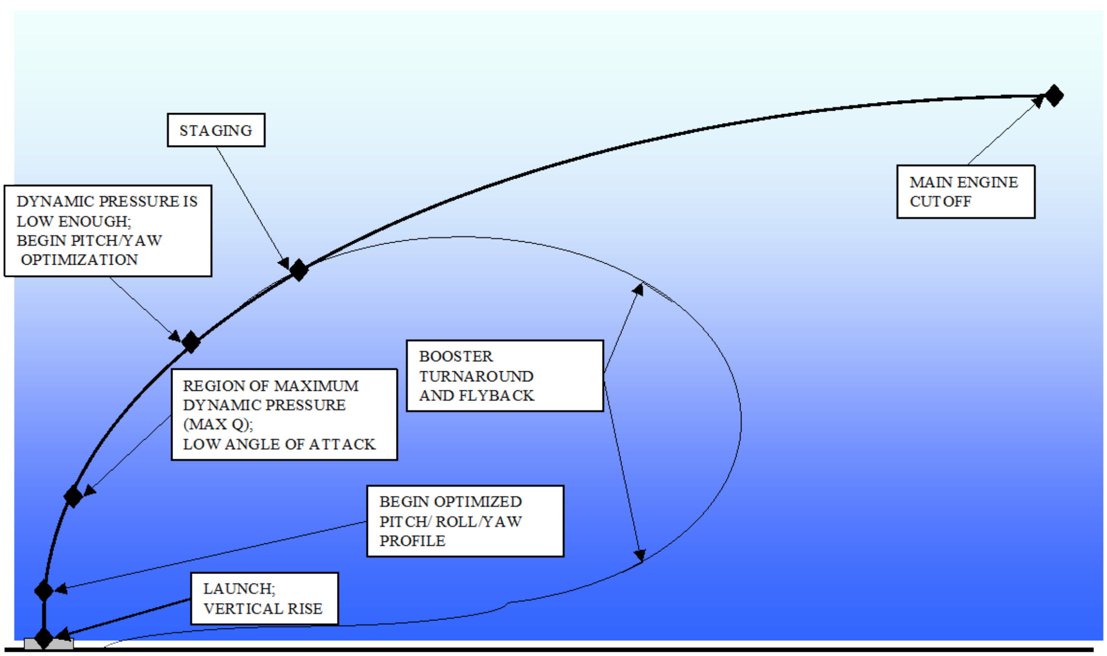


Figure 37. Typical Ascent Trajectory
[SLaTS Course -Trajectories, 2010]

Control System Design and Responses

Once a baseline trajectory is determined along with the rigid body aerodynamic characteristics, we can accomplish a control system initial design and determine its 3-sigma responses to system parameter uncertainties and natural environments. These responses become inputs to the thermal and loads community for calculating associated induced environments. Figure 38 illustrates the initial control design/response process. Figure 39 is a typical control response calculation process. The lower left hand portion of the figure is the output of a Monte Carlo analysis of the various parameter uncertainties and winds where each circle represents an individual run. The plot is for q-alpha and q-beta at a given Mach number, which are indicators of aerodynamic load on the vehicle. Plotting an envelope around the individual runs for each Mach number and combining the results produces the squatcheloid shown on the lower right side of the figure. This squatcheloid is an envelope, usually at the 3-sigma level, of the q-alpha and q-beta combinations on the pitch and yaw planes of the launch vehicle trajectory plotted versus Mach number. The results of the control system design and response analysis, along with the previous data discussed, become the inputs that are used by the loads and thermal analysts to derive their respective induced environments.

1. **Based on configuration, establish control gains and and control frequency. (Chapter 10.2)**
   - **Set gains to provide adequate response without incurring flexible mode stability problems.**
   - **Set gains to obtain desired balance of attitude response, drift response, and load relief.**
   - **In simulation, include details appropriate to design maturity, e.g., flexible modes and filters**
2. **Develop control responses with wind disturbances and parameter variations to determine induced environments.**

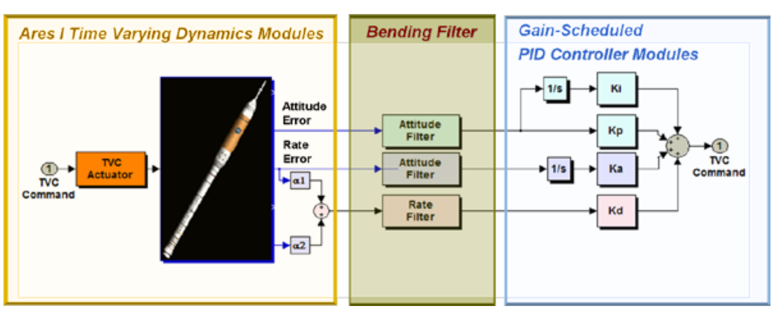


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Figure 38. Control System Initial Design and 3 Sigma Response Calculations
[SLaTS Course -Control, 2010]

Response – Design Conditions for Loads

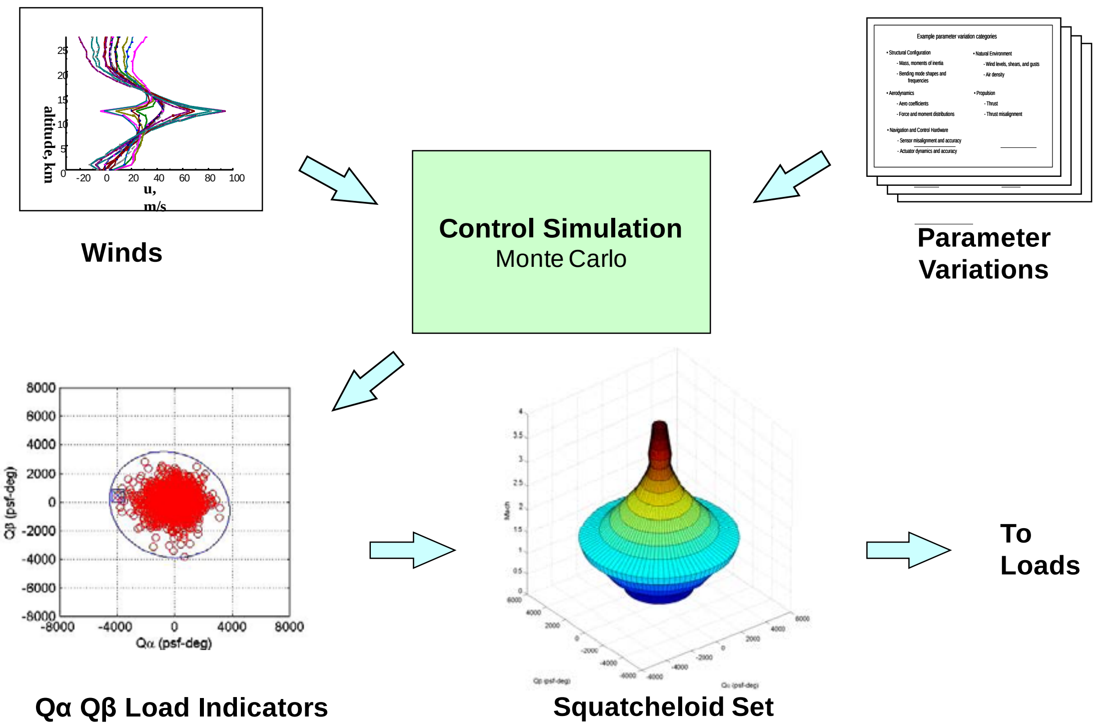


Figure 39. Typical 3-Sigma Control Responses for Induced Environments Determination

[SLaTS Course - Control, 2010]

Loads

Using the data generated by the analyses shown above, external loads are calculated for each mission event. These calculations usually require different models for analysis of each event and must include any additional parameter uncertainties not considered in the previous analysis. Figure 40 is a typical example of major sources of loads for a launch vehicle and Figure 41 is a flow diagram of the basic process for loads determination.

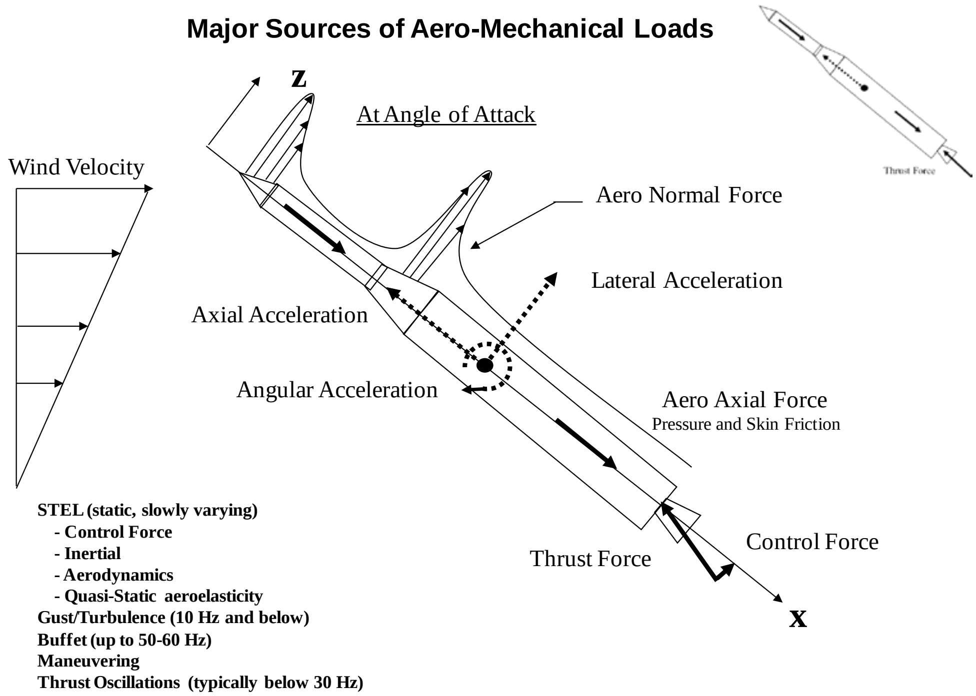


Figure 40. Basic Load Sources for a Launch Vehicle
[SLaTS Course - Loads, 2010]

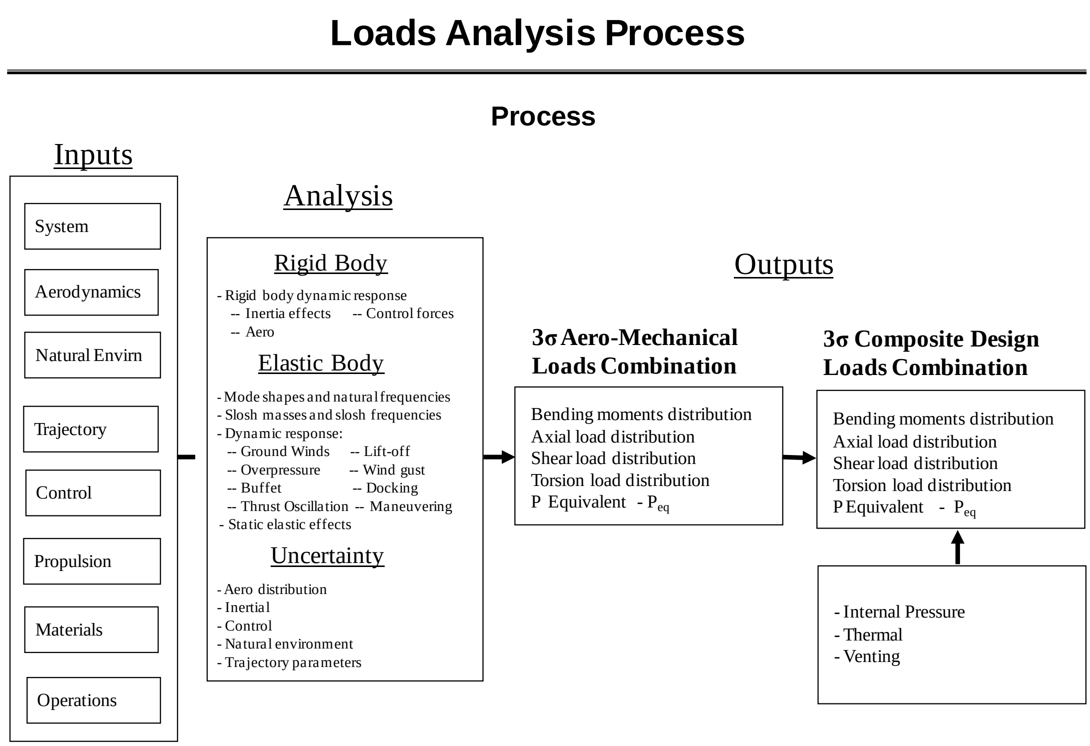


Figure 41. Basic Loads Analysis Process for a Launch Vehicle
[SLaTS Course - Loads, 2010]

Examples of major loads design considerations for various flight events are:

- **Rollout**
  - Crawler speed
  - Wind criteria
- **Prelaunch**
  - Stay damping & stiffness / active control
- **Liftoff**
  - Wind criteria
  - Stay & damper soft release
- **Ascent - First Stage Flight (FSF)**
  - STEL (Static Elastic)
    - In-Flight Load Relief – IFLR
    - Day-of-Launch – DOL
    - STEL dispersions in Loads Combination Equation (LCE)
    - Wind persistence – more balloon launches
  - Gust
    - Turbulence model
  - Buffet
    - “Borrow” capability from STEL
  - Maneuvering
    - Steering changes
- **Staging**
  - Transients
  - Booster tumble motor firing
- **Ascent - Second Stage Flight (SSF)**
  - Ignition sequence timing
  - Ignition gimbaling
  - Tighter CG control

All the various load events analysis results are presented as shear, moments and then combined into what is normally called P-equivalent or running loads. Figure 42 is a typical P-equivalent load plotted versus the launch vehicle length. Since the external loads are one of the major drivers on vehicle weight and many of the operational procedures, it is mandatory that the project managers understand and carefully manage these activities. Here again we are dealing with some of the major integration activities and how the total system is balanced.

Overall Combined Envelope Comparison

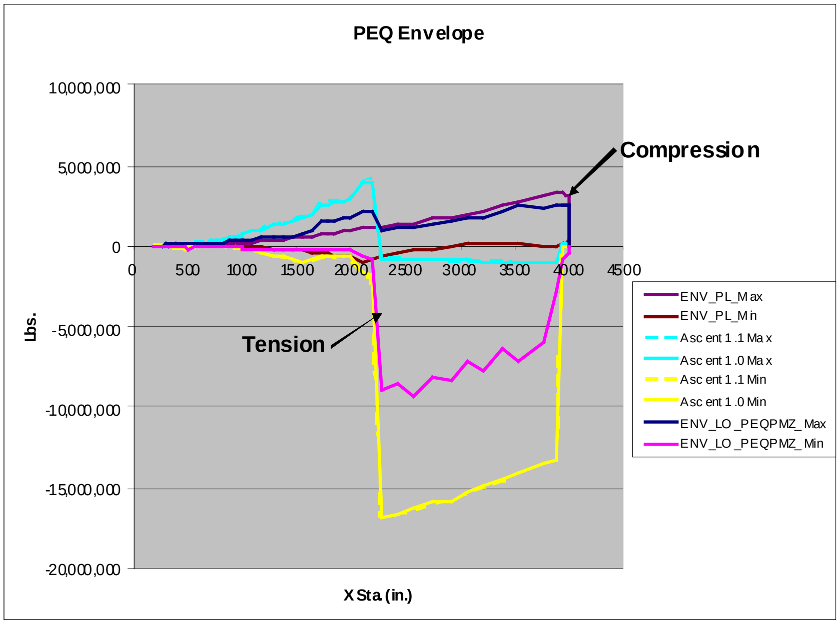


Figure 42. P-equivalent Load for a Typical Launch Vehicle
[SLaTS Course - Loads, 2010]

Thermal Environments

The next main driver for induced environments is thermal. Thermal environments have their source in aero heating, plume heating, power systems, human presence etc. as shown on Figure 43. Typical thermal environments encountered by Shuttle during ascent flight are shown on Figure 44. Determination of the thermal environments requires many inputs as illustrated on the left hand side of Figure 45. The systems integration job dictated by this large number of interfaces for inputs and the corresponding outputs to various design groups is complex and a challenge to managers. The thermal environments impact many design and operational requirements and are a major driver on the system and subsystem design and operations. Again as in loads different models have to be developed and analyzed for each of the major mission events. Numerous and complex tests are required to verify the environments and are a part of the validation and certification a system for flight.

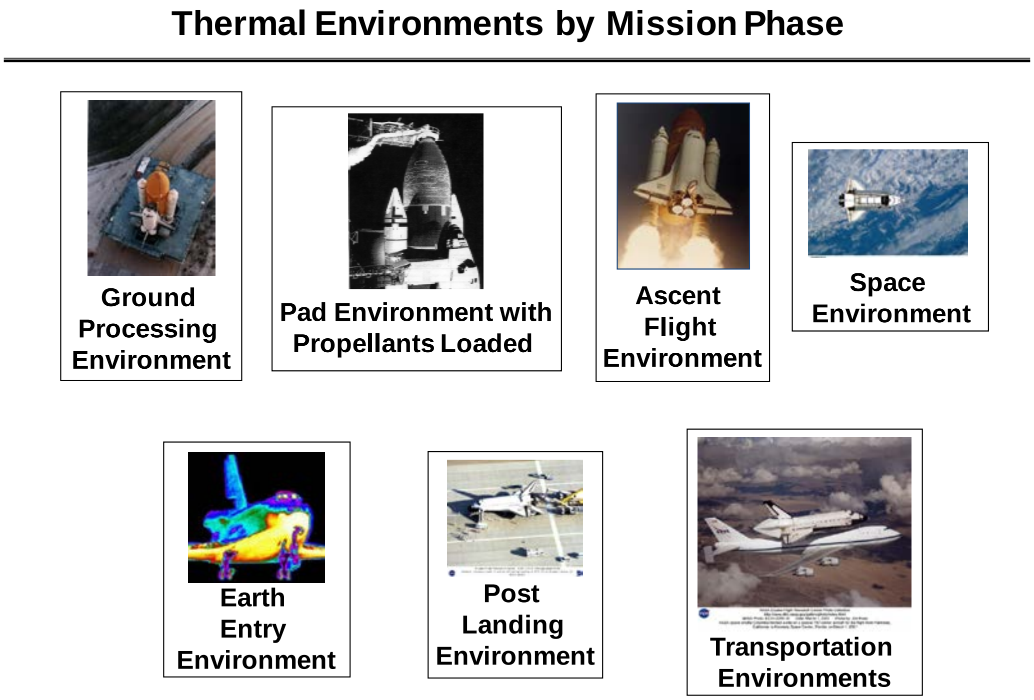


Figure 43. Typical Sources for Thermal Environments
[SLaTS Course - Thermal Environments, 2010]

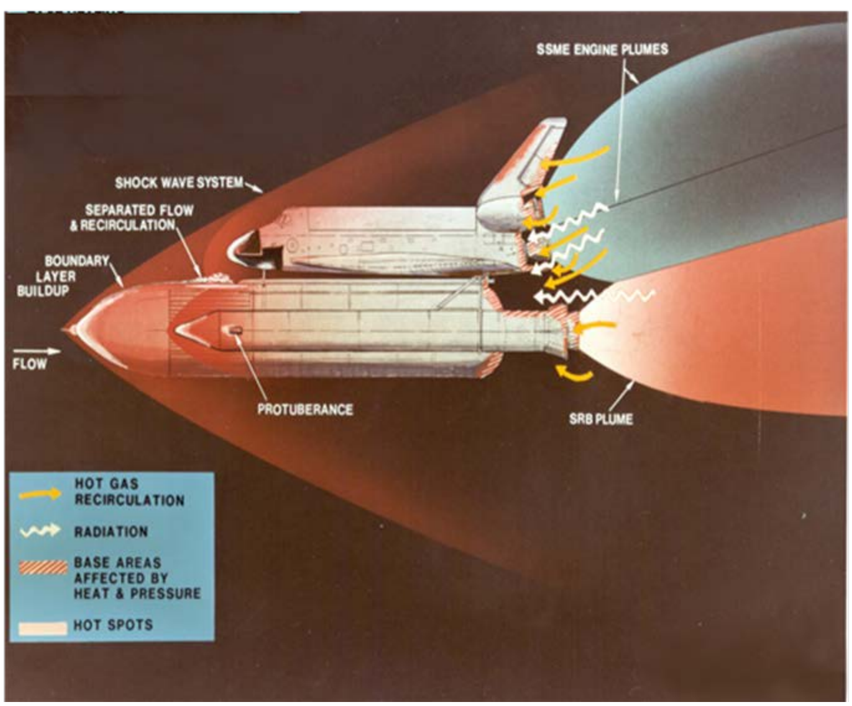


Figure 44. Typical Thermal Environments Encountered by Shuttle During Ascent [SLaTS Course -Thermal Environments, 2010]

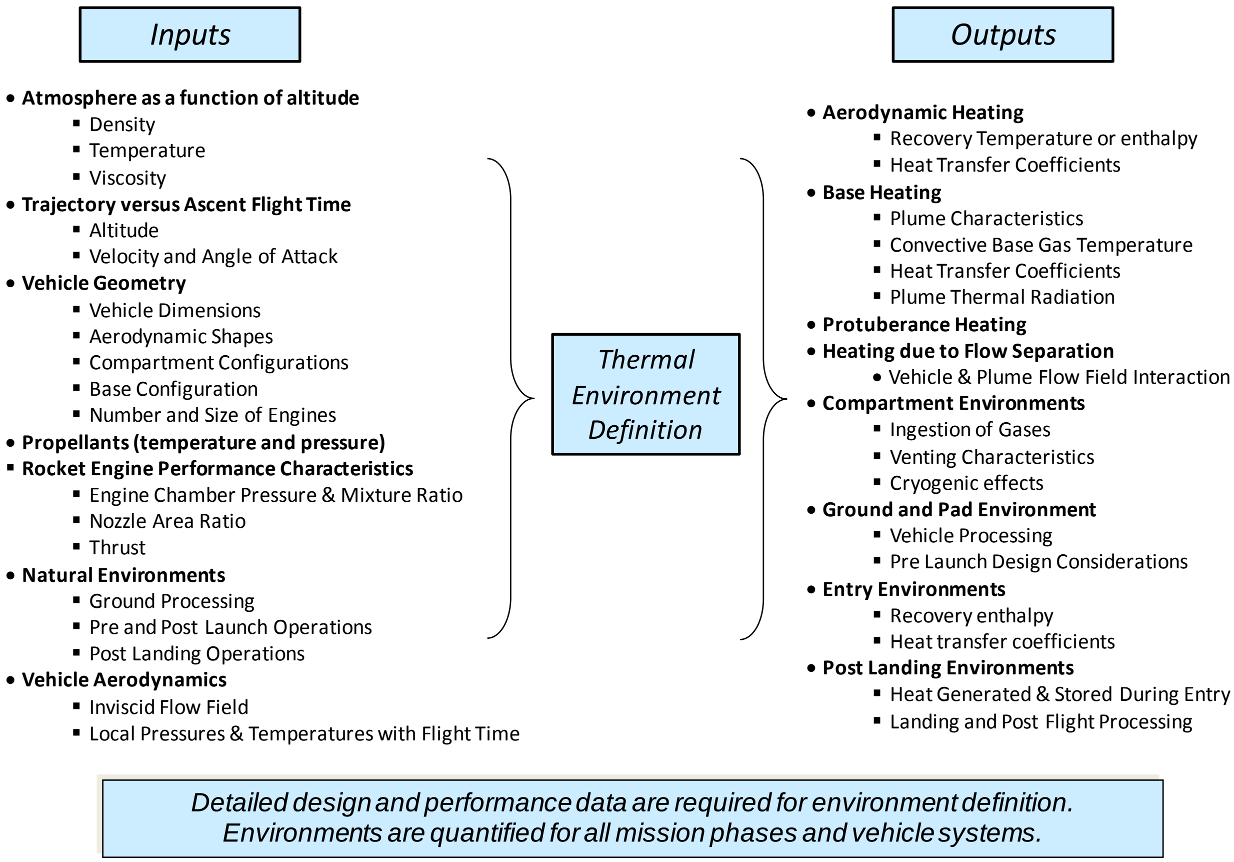


Figure 45. Inputs and Outputs of the Thermal Environments Determination
[SLaTS Course - Thermal Environments, 2010]

We have discussed only some of the induced environments as examples of the project manager's task of determining the induced environments. Once these tasks have been performed for all the induced environments they are combined together to form the formal set of derived requirements,

3. Derived Requirements Summary

Combining together all the induced environments and the other requirements that result from balancing the system provides the basis for determining a formal set of derived requirements. These requirements are then levied on the system to design or modify the design of the system, the subsystems, and components. Figure 46 is a partial listing of categories of some of these requirements by subsystems. This is a very complicated and formal process that requires detailed attention by management as well as by all the practicing disciplines. These requirements become the drivers for the design and for operations of the project.

- Propulsion
  - -- Thrust, I_{sp}, Propellants, Weight, Size, MR, Throttle, TVC, Gimbal, No. Engines, Natural and Induced Environments, Interfaces, etc.
- Avionics
  - -- Natural and Induced Environments, Interfaces.
  - -- *Electrical Power*: Power Profile, Fault tolerance, Redundancy, and Reliability.
  - -- *RF Communication:* Data Transfer, Time Space Position Information/Tracking, Range Safety, Flight Termination, Voice, Video, etc.
  - -- *Electro Magnetic Environmental Effects:* Protect Against - Radiated Emissions, Radiated Susceptibility, Conducted Emissions, Conducted Susceptibility.
  - -- *Command an Data Handling*: Sensor Processing, Algorithm Hosting, Avionics System/Architecture, Measurement and Command Lists, etc.
  - -- *Sensors and Instrumentation:* Type, Sensitivity, Stability, Selectivity, Accuracy Repeatability, Easy to Fabricate, Min Hardware requirements, Reversible, and Fast Response Time.
  - -- *Range Safety System:* AFSPMAN91-710, Security, Reliability, Trajectory, External Shape, Control System layout and Authority, Propellant types.
- Software:
  - -- Mission and Project Requirements: Spacecraft, Instruments, Operations, Performance, Schedule, Funding
  - -- Mission Systems Engineering: Flight Hardware Redundancies, Onboard Autonomy, Onboard Failure Handling Philosophy, Vehicle System and Fault Management
  - -- Guidance, Navigation & Control: GN&C Hardware Decisions, Specs. & ICDs, Control Modes, Control Algorithms, Control Options
  - -- Science Instruments: Data Rates, Interfaces to s/c, Data Handling, Data Processing, Algorithms, Event Handling
  - -- Science & Mission Operations Data Flows, Planning/Scheduling, Ground Contact Strategies
  - -- Electrical Subsystems Flight Data System Architecture Specs. and ICDs (RF, CPUs, memory, buses, data storage, power)
  - -- FSW Test, Maintenance & Remote Troubleshooting Strategies: Diagnostics, Flight Database, Loads, Dumps
  - -- Special Hardware/Software I&T Requirements: Direct ground\crew commanding of flight hardware
  - -- Pre-launch and Launch Requirements: Launch-unique Configurations, Launch Vehicle Separation, In-orbit Sun Acquisition
- Structures
  - -- Architecture, Size, Propellants, Weight, Materials, Manufacturing, Operability, Sensors, Subcomponents, Secondary Structures, Natural and Induced Environments, Engine Mountings, Interfaces, etc.
- GN&C
  - -- Natural Environment
  - -- Vehicle Configuration and Structural
  - -- Performance and Trajectories
  - -- Aerodynamics
  - -- Structural Analysis
  - -- Propulsion
  - -- Thermal
  - -- Avionics and Electrical Power
  - -- Mechanical Systems
- Thermal
  - -- Thermal Environment
  - -- Natural and Induced Environments
  - -- Structural System
  - -- Propellant System
  - -- Pressurization System
  - -- Engine Systems
  - -- Propellant Transfer Systems
  - -- Avionics Subsystems
  - -- Payload Accommodations
- All Systems and Subsystems
  - --Ilities; Reliability, Maintainability, Safety Operability, Quality, ...
  - -- Cost

Figure 46. Example Categories of Refined Derived Requirements for Subsystems/System

C. Subsystem and System Design

1. Subsystem Design

Figure 47 is a flow diagram for the process that the subsystems employ to impact the design as a result of the flow down of the derived requirements. Notice that there is balancing of the system and the determination of additional requirements which are then flowed back to the system. Shown on Figure 48 are typical subsystem design areas. Illustrated are only the Propulsion, GN&C, Structures, Thermal, Avionics, and Life Support subsystems. Others are added as dictated by the characteristics of the project. Management of the activity is critical to the success of the program and or project. Figure 49 is a pictorial of these subsystems for a typical launch vehicle. Other space systems such as spacecraft would have a similar list. These areas will be addressed in more detail in the following sections.

Design and refine subsystems

Identify requirements on other subsystems and system

Determine subsystem attributes including sensitivities

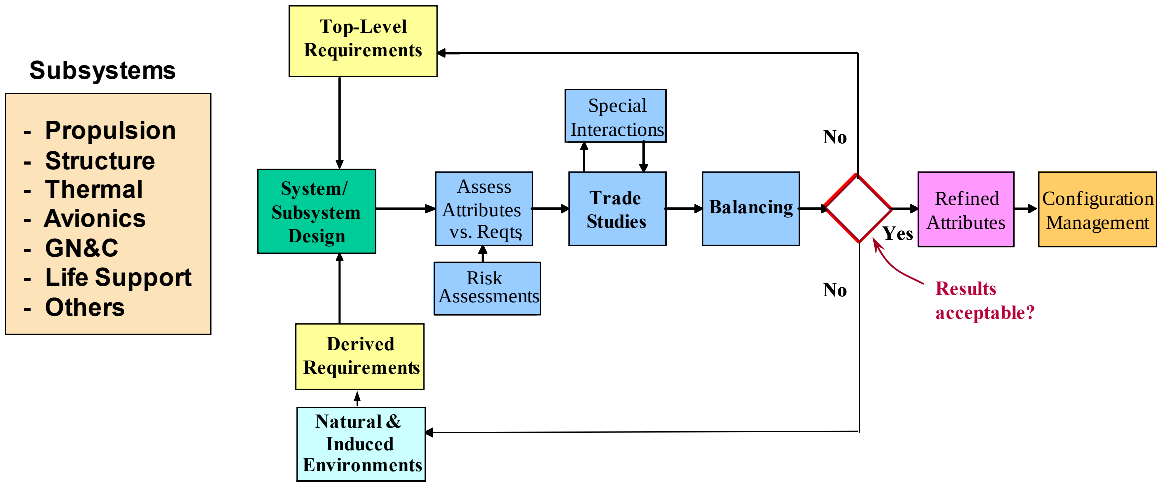


Figure 47. Application of Derived Requirements to Subsystem Design

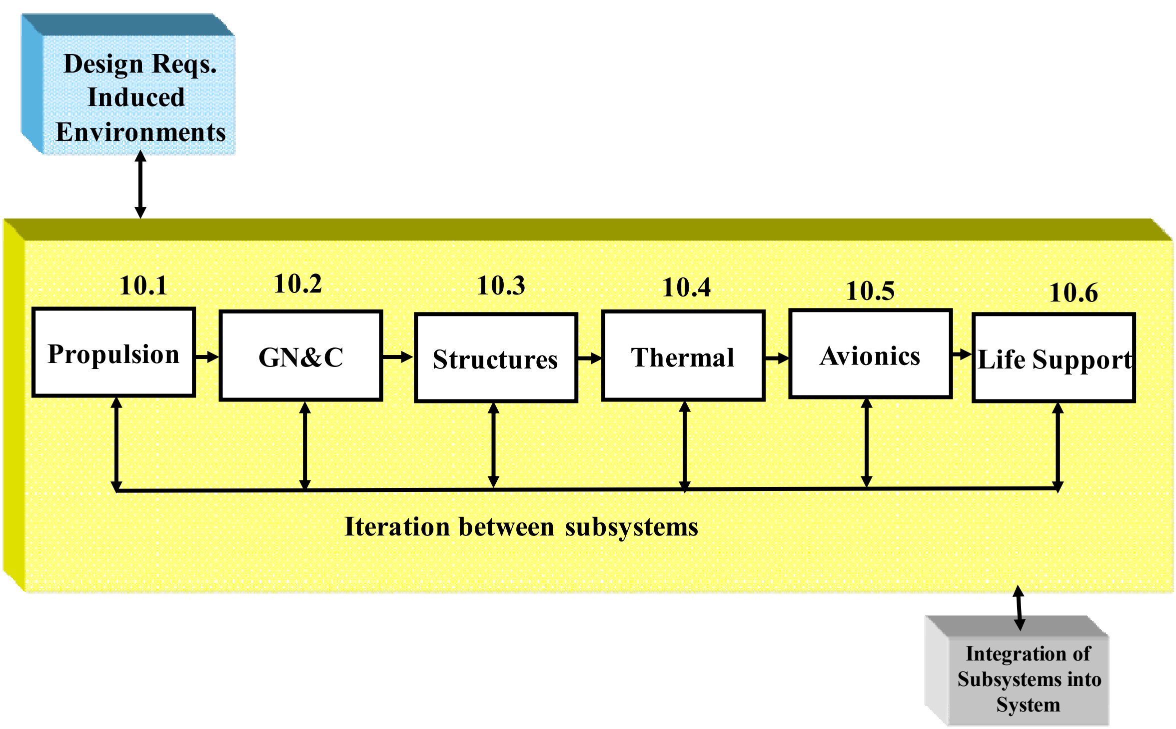


Figure 48. Typical Subsystems that Require Design Activities in the Process

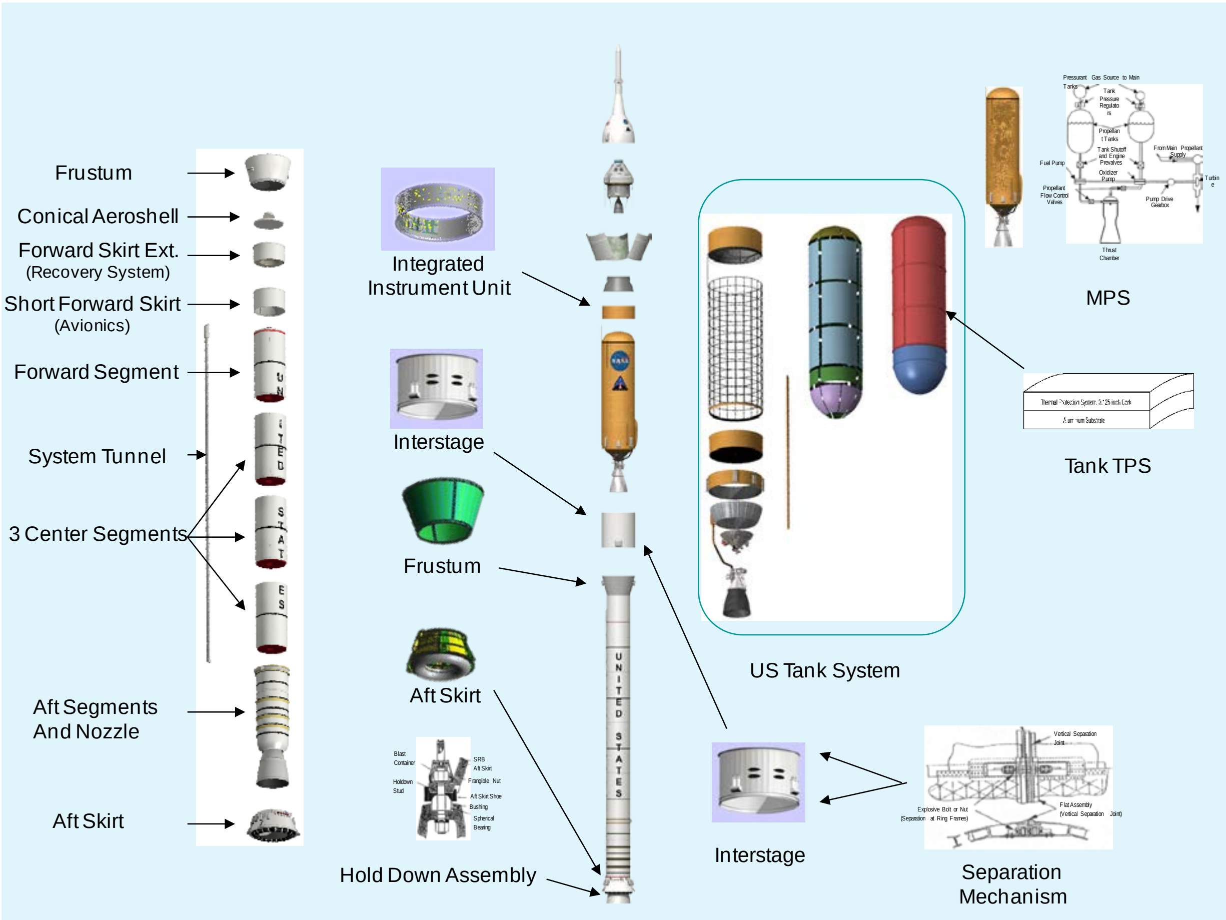


Figure 49. Typical Subsystems of a Launch Vehicle – Ares I Example

2. Example Subsystems

Several of the subsystems will be discussed in more detail in the following sections including their characteristics, options or trade areas, and the reintegration activities that are required to balance the system in the most efficient manner. The following subsystems will be briefly discussed:

a) Guidance, Navigation, and Control (GN&C)
b) Propulsion Systems
c) Structures
d) Thermal
e) Avionics

a. Guidance, Navigation, and Control (GN&C)

The GN&C system guides the vehicle from launch to the desired orbit insertion in a stable manner while maximizing payload mass delivered, subject to constraints on structural and thermal loads. The navigation system continually estimates, based on suites of sensors and Kalman filters, the position and attitude of the vehicle. Based on the estimation of the navigation system, the guidance system continually reprograms the guidance path to the most efficient direction to the target in space. The control system uses this path angle command to keep the vehicle oriented along the guidance path while maintaining acceptable dynamic response to disturbances. The control system is also responsible for maintaining the vehicle stability for rigid body responses, elastic body responses, propellant sloshing and aeroelasticity. Additional functions can be added such as wind biasing and load relief control to reduce weight or increase launch availability. These activities become additional parts of the balancing the system that must be considered.

Figure 50 illustrates the basic elements of the control system, including sensors (inertial measurement units, rate gyros, accelerometers); software in the flight computers containing navigation filters, guidance programs, control laws with appropriate gains and filters; and control effectors for control forces. Control effectors include thrust vectoring systems (typically actuators and hydraulic power units) and reaction control thrusters. Selecting or designing the control system hardware and software/computer provisions is an interactive activity with the control law / dynamic response design.

Basic Control System Elements

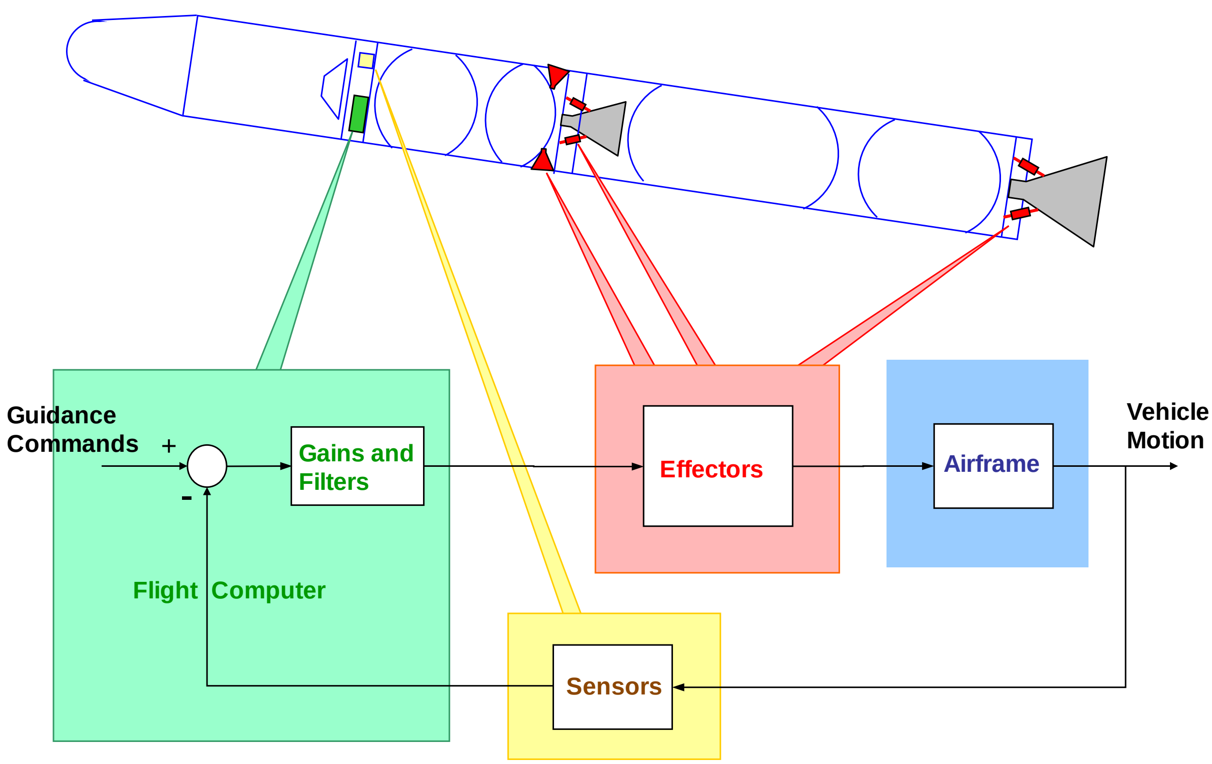


Figure 50. Control Functions and Elements for Implementing the Functions
[SLaTS Course - Control, 2010]

b. Propulsion

The first function of propulsion systems is to provide the energy required to propel the system in space. For a launch vehicle this is a very high performance and concentrated power density system that is very complex and fraught with high sensitivities and many unwanted interactions. Normally the main propulsion can be separated into liquid and solid systems, with further categorizations of these two basic systems into various implementation options. Auxiliary propulsion systems used for vehicle control and other functions are separate and challenging additional systems. Figure 51 is an example of a liquid main propulsion system showing its functions and subsystems along with some of the design issues that drive the system.

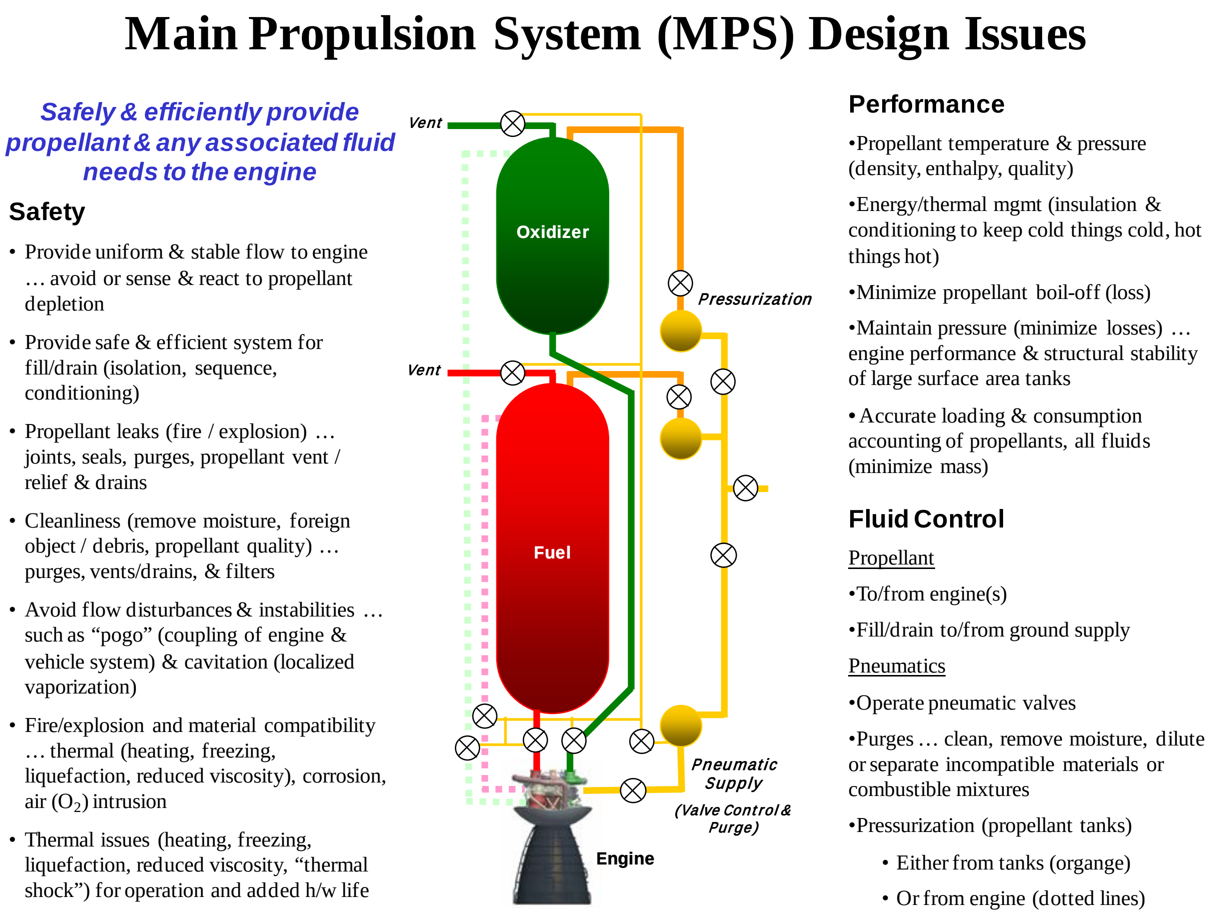


Figure 51. Liquid Main Propulsion System Functions and Design Drivers
[SLaTS Course - Propulsion, 2010]

The classic example for efficiency of liquid propellant systems is the SSME. As noted earlier, a turbine blade that is about the size of a human thumb generates 550 horsepower and operates at a temperature of 1800 degrees Rankine. The high pressure fuel turbopump is about 2 feet long and 18 inches in diameter. It spins at 30,000 RPM and generates 70,000 horsepower. The turbine end of the pump is at 2,000 degrees Rankine while the other end that pumps liquid hydrogen runs at -422 degrees. Development of the SSME incurred 38 major failures during testing that were very costly in material, hardware, facilities and schedule. Several redesign cycles or block changes were made to eliminate many of the interaction problems that occurred during development. Managing these complex systems requires the best available systems engineering and technical integration processes and techniques. The following is a list of some trades and considerations for the design of liquid propulsion systems:

1. Engine cycle
2. Propellants
3. Thrust level vs. number of engines
4. Thrust to weight
5. Isp vs. tank size
6. Materials and manufacturing options
7. Verification/certification

Figure 52 is a cross section view of a solid rocket motor propulsion system. Illustrated is how the internal grain pattern is shaped to create variations of thrust versus burn time. Other solid propulsion design issues involve aspect ratio, grain properties, insulation, nozzle thermal protection, igniter design, thrust vectoring, case materials, and manufacturing processes.

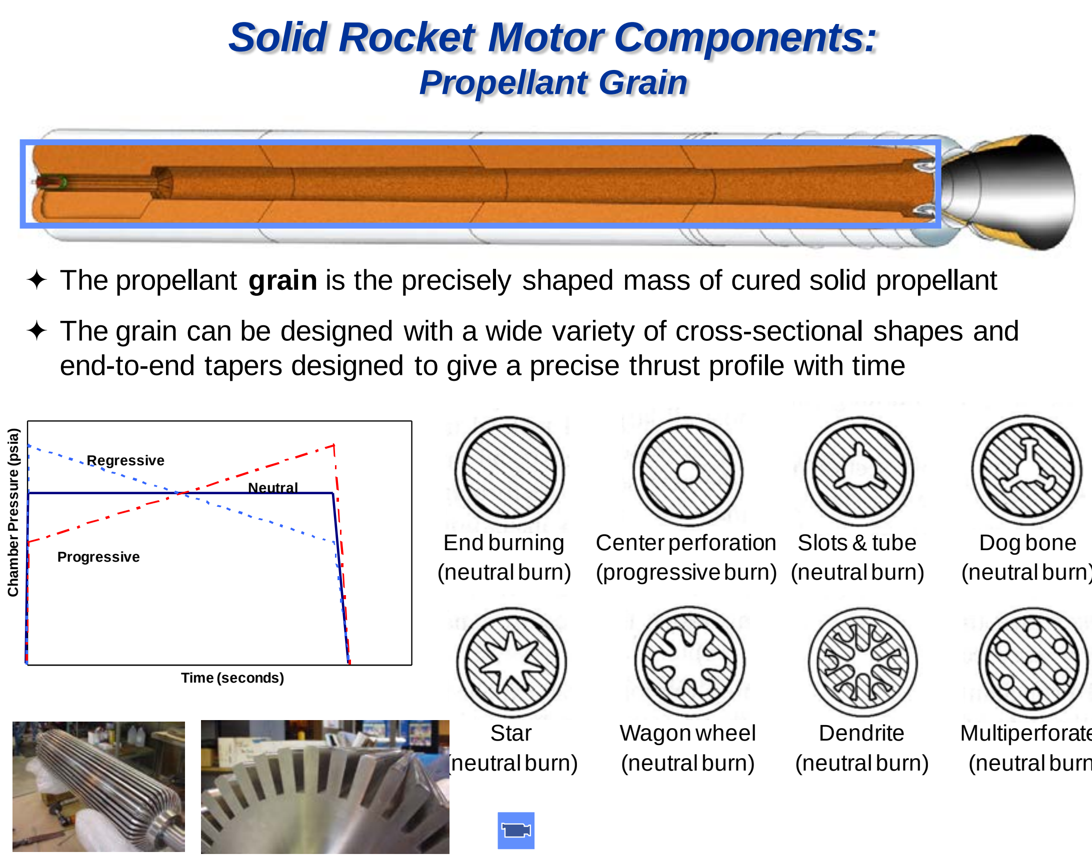


Figure 52. Solid Rocket Motor Components and Various Grain Patterns to Produce Precise Thrust Profiles with Time
[SLaTS Course - Propulsion, 2010]

Auxiliary propulsion systems are used to perform basic control functions when main propulsion systems or aerodynamic control force systems are not available, to provide orbit maneuvering and maintenance functions, and to aid in separation and propellant settling functions. They are the systems used on many orbiting space systems. Figure 53 shows the standard functions and functional implementation of these auxiliary propulsion systems. The table lists the functions, why needed, and typical examples of current implementations.

Common Types of Launch Vehicle Auxiliary Propulsion

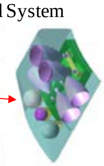
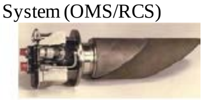
Function	When Needed	Why Needed	Familiar Examples
Roll Control	• When single engine or motor provides main thrust (since no opposing engine can be used to provide roll)	• Antenna orientation • Astronaut horizon orientation, visibility	• Ares I First Stage Roll Control System  
Reaction Control	• When earth-to-orbit vehicle must place payload into orbit • When earth-to-orbit vehicle is staged	• Propellant settling for upper stage engine restart • Assist with stage separation	• Saturn S-IVB Upper Stage Auxiliary Propulsion System 
	• When vehicle provides orbital maneuvering capabilities • When vehicle provides controlled deorbit or re-entry	• Stationkeeping • Orbit adjust • Proximity operations, docking • Unload momentum wheels, if present • Re-entry control	• Shuttle Orbital Maneuvering System and Reaction Control System (OMS/RCS)  

Figure 53. Common Types of Auxiliary Propulsion Systems
[SLaTS Course - Propulsion, 2010]

The propulsion community has established a comprehensive lessons learned data base that is available for designing future systems. Figure 54 is one example of a summary chart of the history of some of the problems and corrective actions experienced by the Space Shuttle Main Engine (SSME). This data base includes most of the corrective actions required during the development program of the SSME. Also available are all the SSME major development failure reports. The design and operation of systems such as SSME are very challenging and are as complex as the design and operation of overall space systems such as a launch vehicle. The efficiency of the propulsion system in conjunction with the structural system are the major drivers in balancing the design of a launch vehicle.

SSME Problem History / Lessons Learned

- **Development process intended to catch and eliminate problems that will compromise ability to meet requirements**
- **Lessons learned from prior programs are invaluable in pointing design team toward areas needing emphasis**

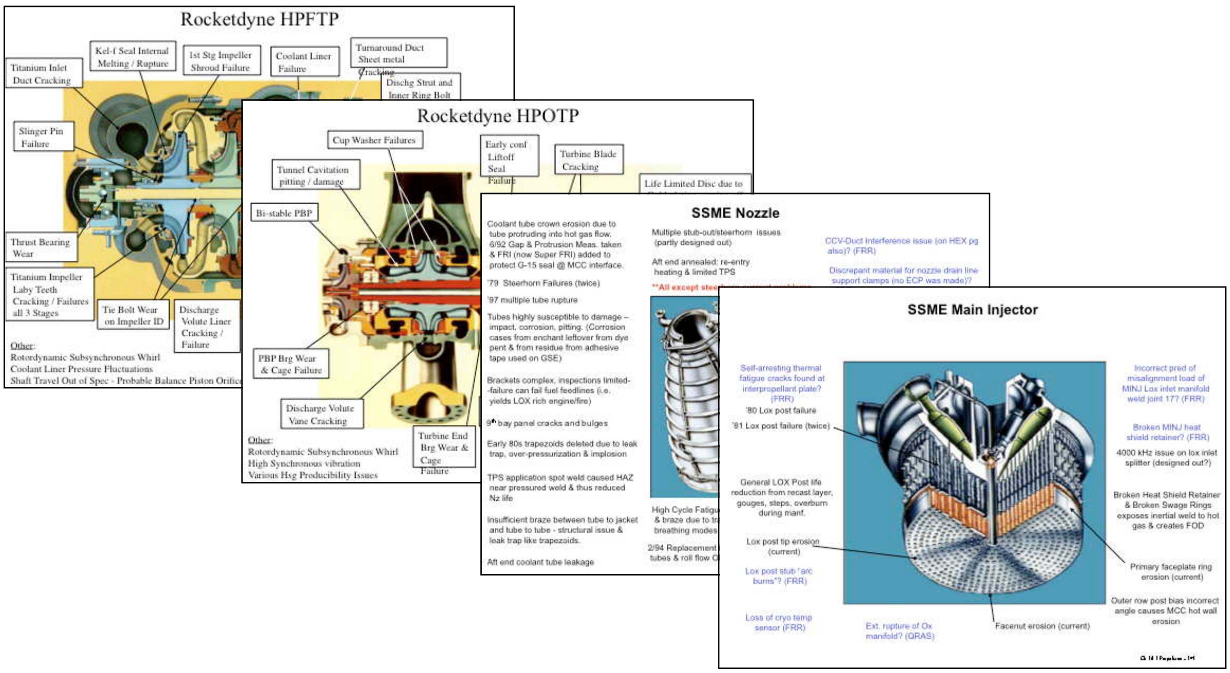


Figure 54. Lessons Learned in Liquid Propulsion Systems / Space Shuttle Main Engine
[SLaTS Course - Propulsion, 2010]

c. Structures

The mass efficiency of structures is a key consideration in the design of launch vehicles and spacecraft. One term that is used for efficiency is mass fraction. Propellant mass fraction is the ratio of the propellant mass to the total loaded mass of the system. Mass fractions of launch vehicle stages typically range from about 0.85 to 0.90.

There are many trades and considerations that have to be conducted and decisions made in structural design. The following is a typical list.

1. Expendable vs. reusable
2. Inline vs. parallel
3. Propellant tank location and configuration
4. Load paths - load lines
5. Thrust structure: Shell vs. space frames

6. Bulkheads: common vs. separate, dome shape
7. Isogrid vs ring frame and stringers, honeycomb, monocoque,
8. Material: metallic vs. composite
9. Welded, bonded, mechanical fasteners
10. Spin formed, break formed, roll formed, age formed, machined, layup

Figures 55-57 illustrate a sample of some of the considerations and trades in structural design. The results of these trades affect not just the structures subsystem but also the total system. Therefore, to be correct, the structural trade decisions must be made from a total system viewpoint.

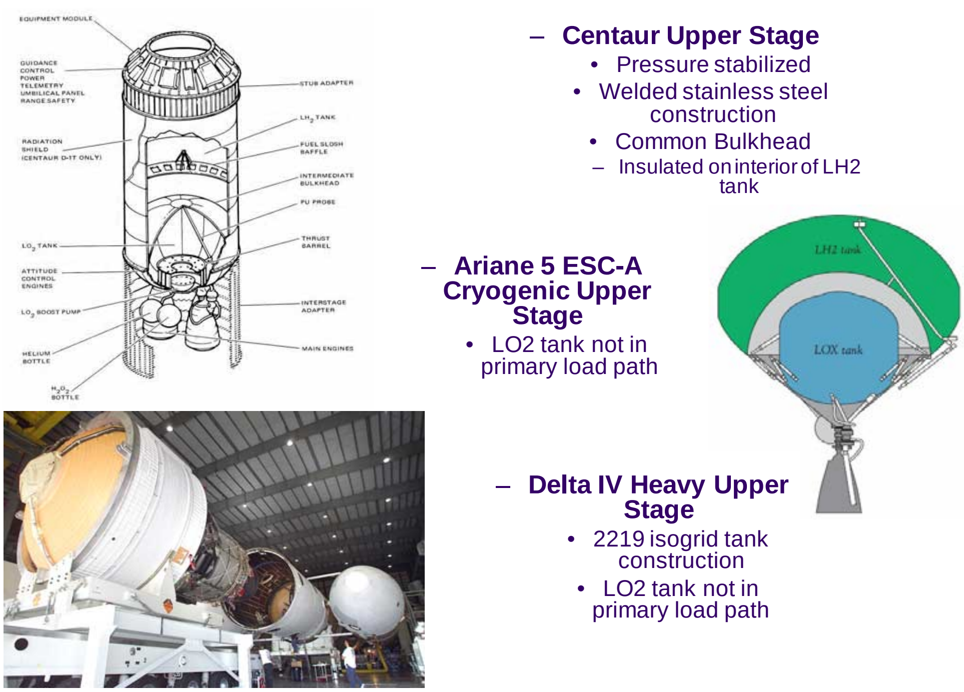
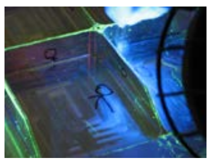
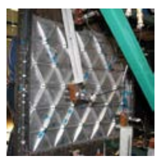


Figure 55. Examples of Structural Design Trades and Concept Selection Options
[SLaTS Course - Structures, 2010]

- **Wall Construction**
  - Unless structure is pressure stabilized or Composite, stiffeners are generally required to prevent buckling
  - Stiffeners may be machined into parent material, bonded, welded, or mechanically attached
    - Mechanical attachment can be costly and is generally limited to unpressurized structures
    - Machined ribs with flanges can be difficult to inspect





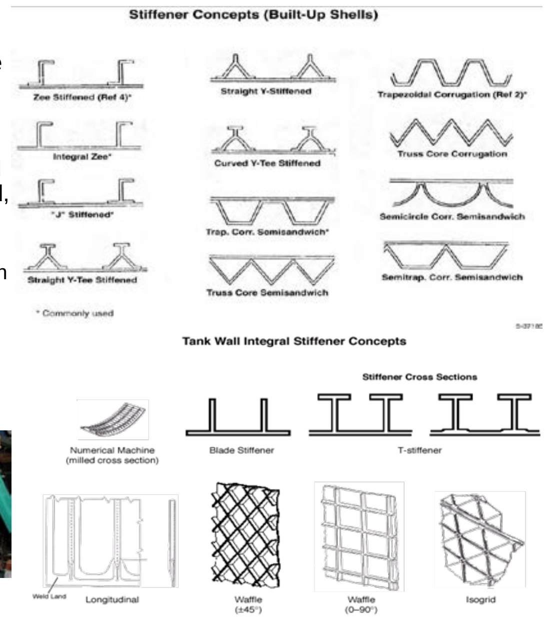
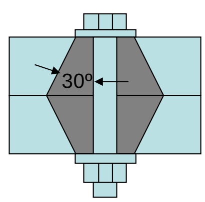
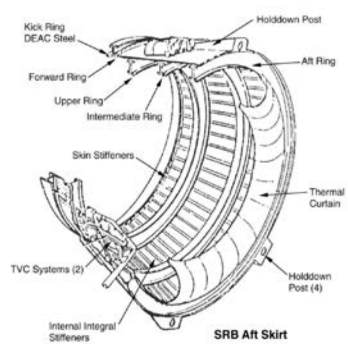


Figure 56. Examples of Structural Design Trades
[SLaTS Course - Structures, 2010]

- **Load path**
  - Care must be used in spreading concentrated point loads
    - Design so re-enforcement thickness spreads the load (shear lag)
    - Best to end re-enforcement of eccentric loads at a structural ring to reduce radial loading into the skin
    - Examples: SRB attachment points





- **Load path and stiffness**
  - Loads go to stiffer paths in the direction of loading
    - Load will be a ratio of the stiffness
      - Increasing thickness of weld lands can draw load
    - Holes and gaps are areas of no stiffness which result in higher stresses at the edges/corners that need re-enforcement
      - Access Doors
      - Gaps in separation rings
    - Consider impacts of stiffness across component joints between tanks and skirts
    - Repairs or reinforcements should not be made overly stiff

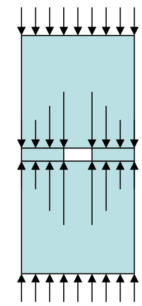


Figure 57. Load Path Considerations in Structural Design
[SLaTS Course - Structures, 2010]

d. Thermal Systems

Thermal systems have many functions, for example: maintaining propellant condition, keeping materials temperature within its capability limits, maintaining human environments, equipment environments, etc. Figure 58 is a block diagram of the basic thermal design process. It starts with requirements, followed by determination of induced environments, the identification of design and material options, trade studies, design and verification. Figure 59 is a checklist to help in managing the process. Figure 60 provides some typical examples of the heating and thermal protection and control systems.

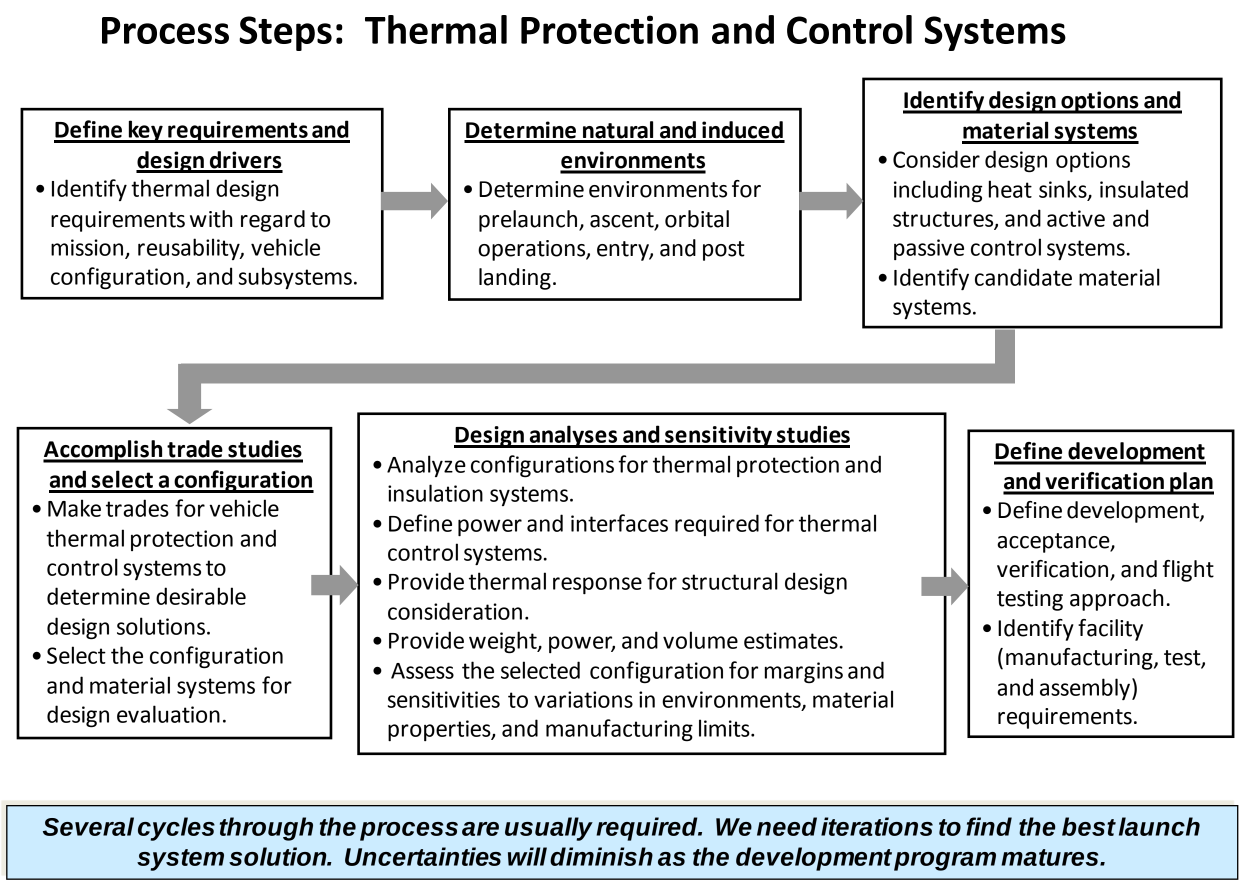


Figure 58. Thermal Protection and Control Systems Design Process
[SLaTS Course - Thermal Systems, 2010]

System/Environment	Consideration	Historical Derivation/Source of Requirement
Propellant system	Control temperature and pressure Determine operational timeline	Cryogenic conditions, maintain structural limits Facility propellant transfer and vehicle conditioning
Pressurization system	Control temperature and pressure Determine operational timeline	Thermodynamic state, maintain tanks within limits Pressurization flow rate, pressure, and temperature
Ascent aerodynamics	Evaluate pressure & temperature Assess altitude and velocity Design for acoustics and vibration	Trajectory design Trajectory design Induced environment
Structures and interfaces	Evaluate pressure & temperature Determine loads, Predict strain	Structures & materials allowable temperature Structural design analysis, Design loads prediction
Terrestrial environment	Evaluate temperature, humidity, precipitation Evaluate wind (ground and flight) Atmospheric pressure/density	Natural environment at launch site Standard atmosphere Standard Atmosphere
Space environment	Evaluate thermal radiation, micrometeoroid and orbital debris environment, and molecular heating	Natural and Space environment, Debris hazard
Entry environment	Evaluate pressure & temperature Assess altitude and velocity Design for acoustics and vibration	Trajectory design Trajectory design Induced environment prediction
Engine systems and components	Determine internal environments Assess pressure and temperature Define fluid constituents/species Evaluate thermal radiation	Propulsion system design Propulsion system design Propellant and combustion product species Propulsion system design
Avionic & payload accommodation	Control temperature & accommodate heat loads	Condition electronics & provide service to payloads

During concept definition, we should analyze the systems and environments shown for sensitivity to expected operating conditions.

Figure 59. Launch Vehicle Thermal Design Checklist
[SLaTS Course -Thermal Systems, 2010]

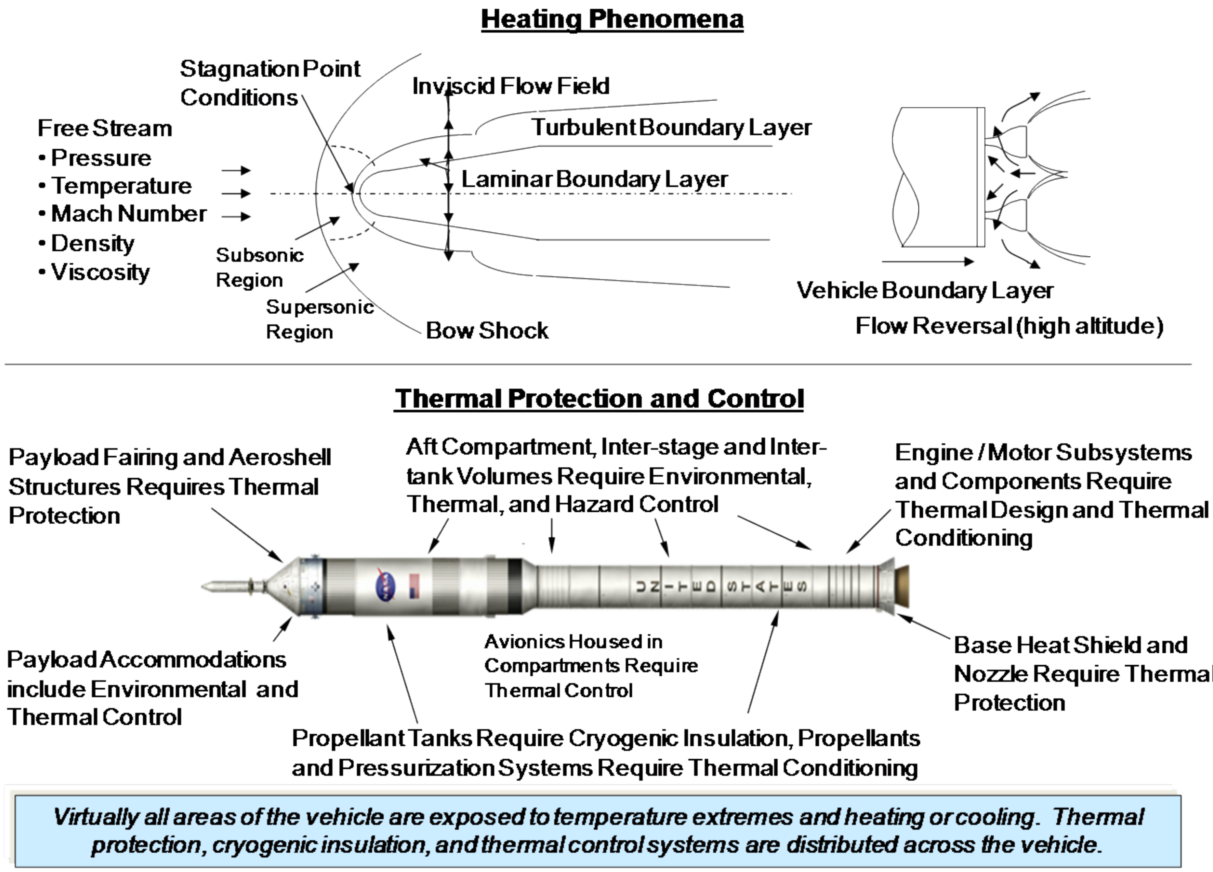


Figure 60. Examples of Heating and Thermal Protection Requirements
[SLaTS Course -Thermal Systems, 2010]

Because of these basic requirements for thermal systems design, the thermal system influences and interacts with most of the other major subsystems. For example, how we fly the trajectory, implement control logic for load relief, etc. can drive the thermal environments and complicate the thermal system design. In many cases thermal is one of the drivers in the selection of materials such as turbine blades and impellers. It is the task of the chief engineer/designer and the project manager to see that the system is balanced among all the subsystems. The task requires that they have an understanding of the major drivers of each of these subsystems.

e. Avionics

We usually think of avionics as a combination of black boxes connected together electrically that magically make things work. If a launch vehicle (LV) were a human body, avionics would be the brain and central nervous system.

The avionics subsystems consists of electrical power systems (EPS), radio communications, electromagnetic environmental effects (E3), command and data handling, sensors and instrumentation, flight software, and range safety. Some of the key issues within each of these subsystems are functionality of the subsystem, cost, reliability, heat rejection, communications, location, mass, and volume. In the design of the avionics system, interactions and interdependencies are critical design challenges.

Figure 61 delineates the Avionics subsystems. The following is an overview of typical activities associated with various subsystems:

a. Electrical Power Systems provide batteries and power conditioning needed to satisfy various requirements along with verification.
b. Radio Communications provide data transfer, time space position tracking (TSPT), range safety/ flight termination system, voice for crewed vehicles, and video through frequency management.
c. Electro Magnetic Environmental Effects (E3)
    1. Radiated Emissions - limits EMR so no interference with on-board receivers.
    2. Radiated Susceptibility - defines limits so equipment will not experience interference from RF transmitters.
    3. Conducted Emissions - limits noise to platform power bus.
    4. Conduct Susceptibility – defines immunity level to preclude interference from power bus noise.
d. Command and Data Handling defines vehicle mode or mission phase of vehicle software, data command processing and distribution, vehicle timekeeping, data-bus management, formatting telemetry, and data storage.
e. Sensors and Instrumentation implements requirements to sense a stimulus then converts it to electrical response which results in an output voltage and then converts it to counts.
f. Software developed for flight, ground, and simulations.
g. Range Safety provides range limit lines, flight termination system, and pyrotechnic locations.

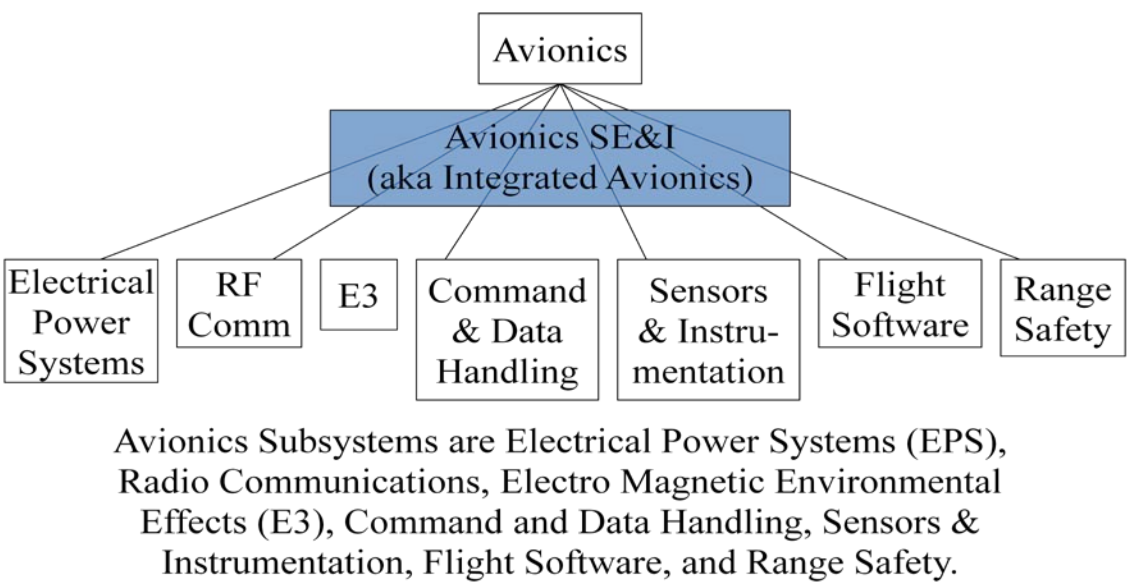


Figure 61. The Functions and Subsystems of Avionics
[SLaTS Course, Avionics, 2010]

The avionics design function includes responsibility for designing the electrical and electronic hardware and software that comprise the avionics system for the vehicle and all the supporting systems as well as all payloads, satellites etc. Therefore it is both the flight systems and the ground support and checkout systems. Typical flight hardware components include the vehicle flight computer, power distribution and control unit, telemetry computers, battery units, inertial navigation system, global positioning system, transmitters, receivers, video cameras and processors, instrumentation, sensors, signal conditioners, cabling, power conditioners, power distributors, rate gyros, and actuator controls, some as indicated on Figure 62.

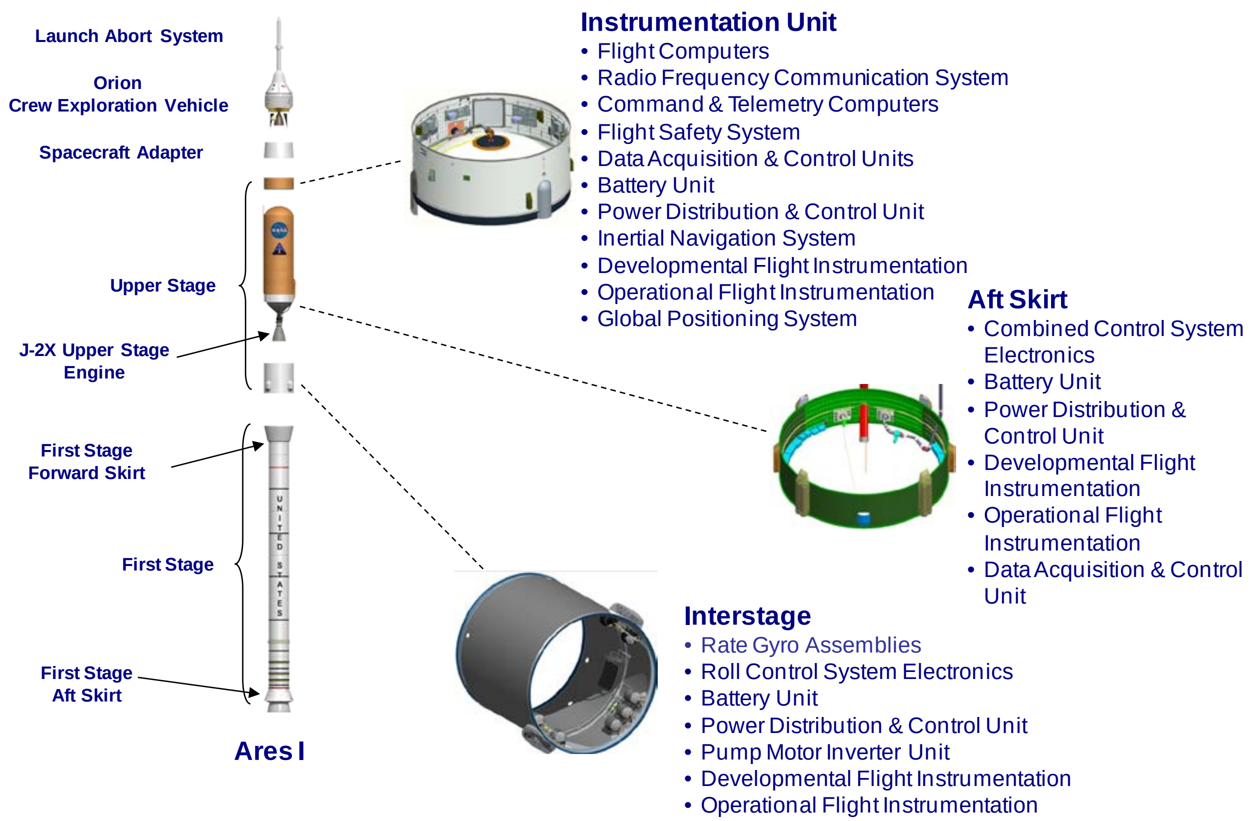


Figure 62. Typical Avionics Components of a Typical Launch Vehicle
[SLaTS Course - Avionics, 2010]

The avionics design function involves the synthesis of the avionics system to meet requirements in two general categories:

(1) Performance of the electrical/electronic systems and

(2) Resource and interface requirements, including cost, reliability, weight, power use, volume, and thermal conditions.

The design of the avionics system involves interactions with disciplines in other design functions including the systems design function. Interaction with the systems design function is vital in determining the requirements for the avionics system. See Figure 63. The systems technical integrator establishes the aforementioned general categories of requirements. Internal to the avionics design function is the avionics system engineering and integration discipline. This discipline is responsible for understanding the requirements for avionics from the systems technical integrator and deriving the more detailed avionics system requirements.

Requirements are allocated and analyses and trade studies are performed. Reliability requirements are considered together with weight, power, volume, and cost to determine the appropriate level of redundancy and redundancy management which is a major driver in avionics complexity. From these requirements, the avionics system architecture is defined. All disciplines within the avionics design function are involved in the architecture definition, but the avionics systems discipline is responsible for assuring that the architecture will meet the overall requirements and constraints. Component requirements and constraints are derived and an electrical, electronic, and electromagnetic (EEE) parts plan is developed.

An important factor at the time of the architecture definition is the determination of the means and extent of verification of the avionics system. Packaging to accommodate the environments is designed, and estimates are made of the power, weight, volume, and thermal characteristics. The collected attributes of the preliminary design are then compared with the avionics requirements and constraints, and the design is iterated until satisfactory convergence or relief from requirements is sought from the systems technical integrator.

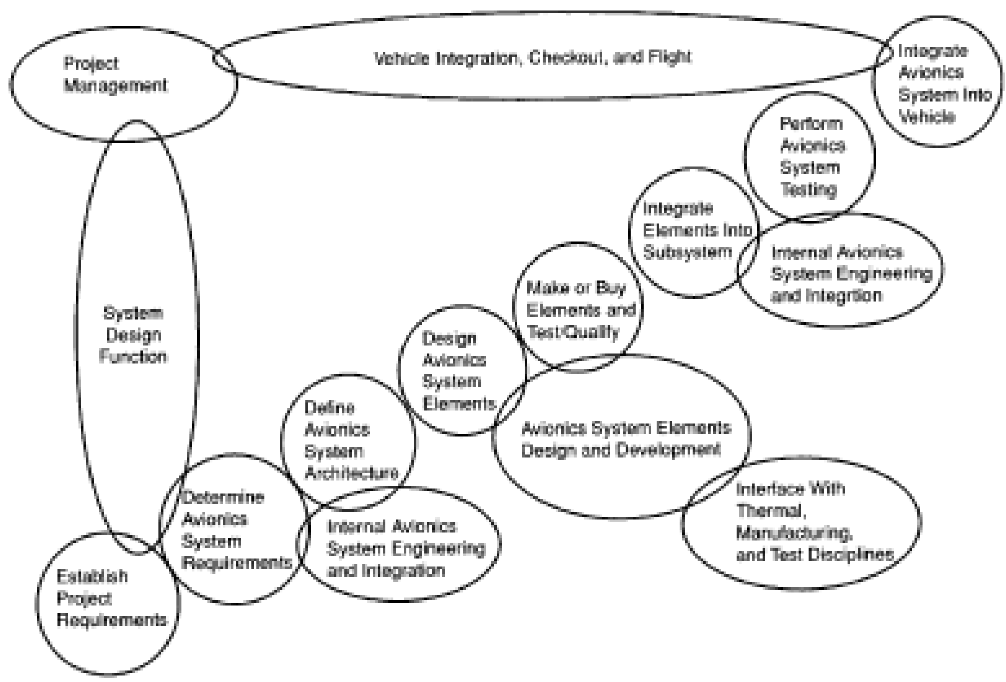


Figure 63. The Major Interactions and Design Flow of the Avionics System
[NASA TP-2001-210992, Avionics - Atherton et. al., 2001]

Two examples of the application of Avionics subsystems are given below. The first pertains to how the hardware and software are applied for the navigation and guidance system. The Avionics subsystems receive signals from the vehicle's sensors, process the signal data, and send commands to the rest of the vehicle, telling subsystems what to do, and informing the ground of what it is doing. Another way to say this is that avionics provides the means in telling the launch vehicle where to go, what to do, checks how it's working, and reports back to the ground system.

The second example is the Space Shuttle SRB RF links as shown in Figure 64. It can be seen that it includes radar tracking, telemetry, satellite and voice communications, and range safety.

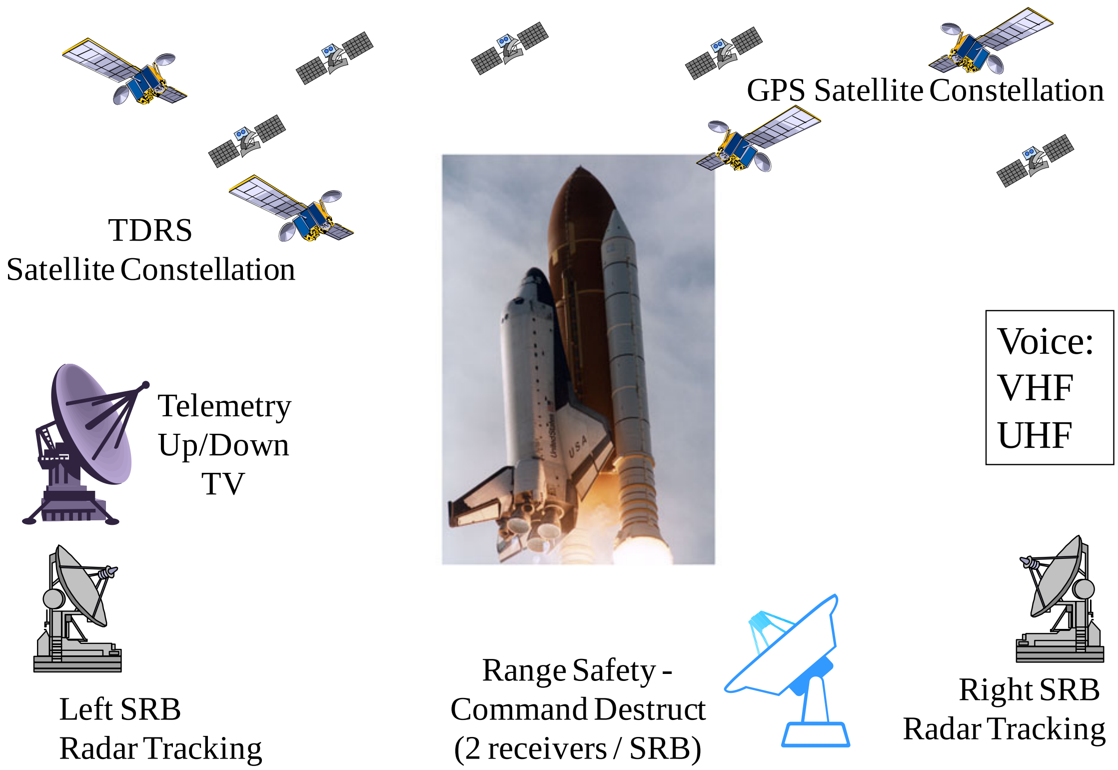


Figure 64. The Space Shuttle Communications System Typical RF Links
[SLaTS Course - Avionics, 2010]

Figures 64 and 65 delineate the inputs, tasks and outputs of two major subsystems of the Avionics system. Figure 65 is an illustration for a typical Communications and Data Handling System and Figure 66 is for a typical Power System. These figures illustrate the level of complexity and required interactions it achieve a flight certified design.

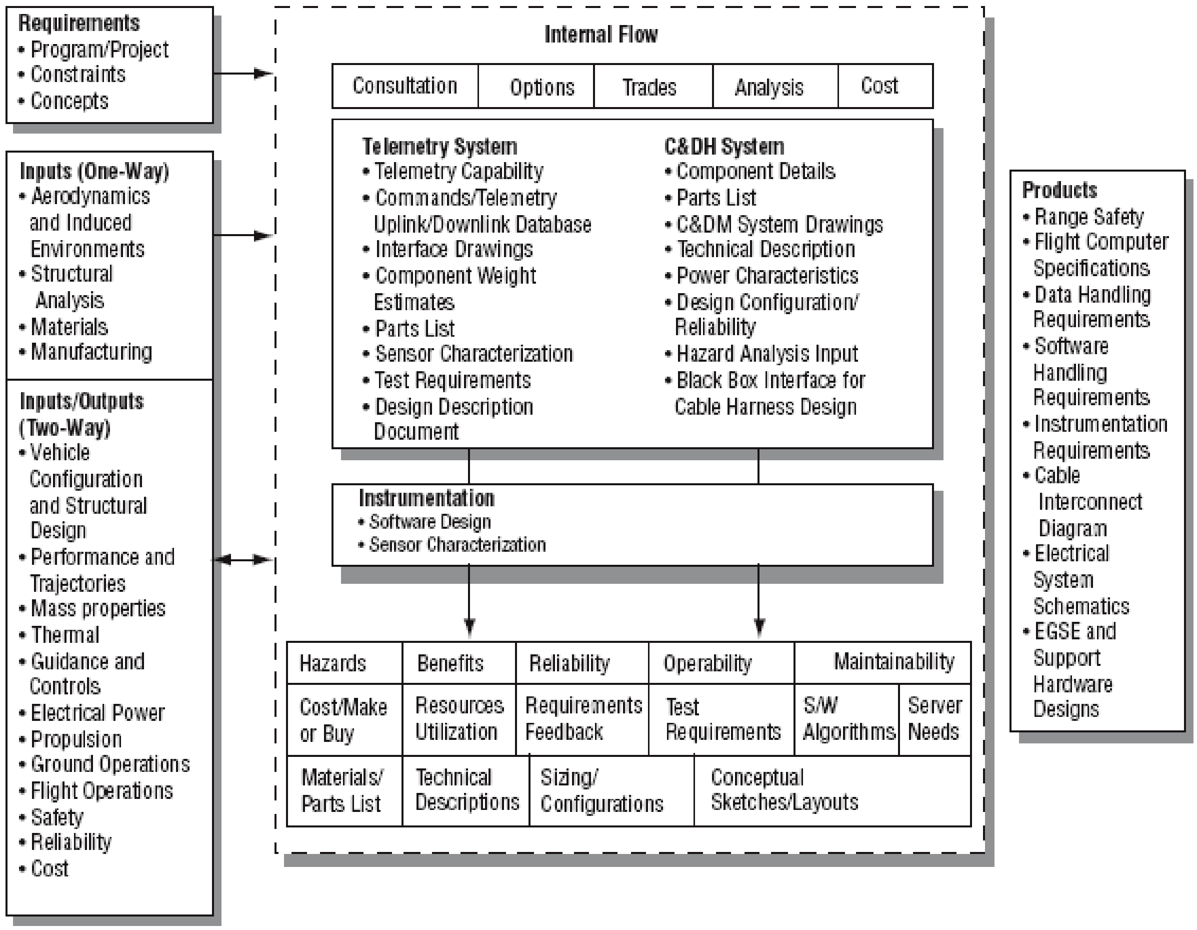


Figure 65. Inputs, Tasks and Outputs of a Typical Communications and Data Handling System
[Humphries et. al., 1999]

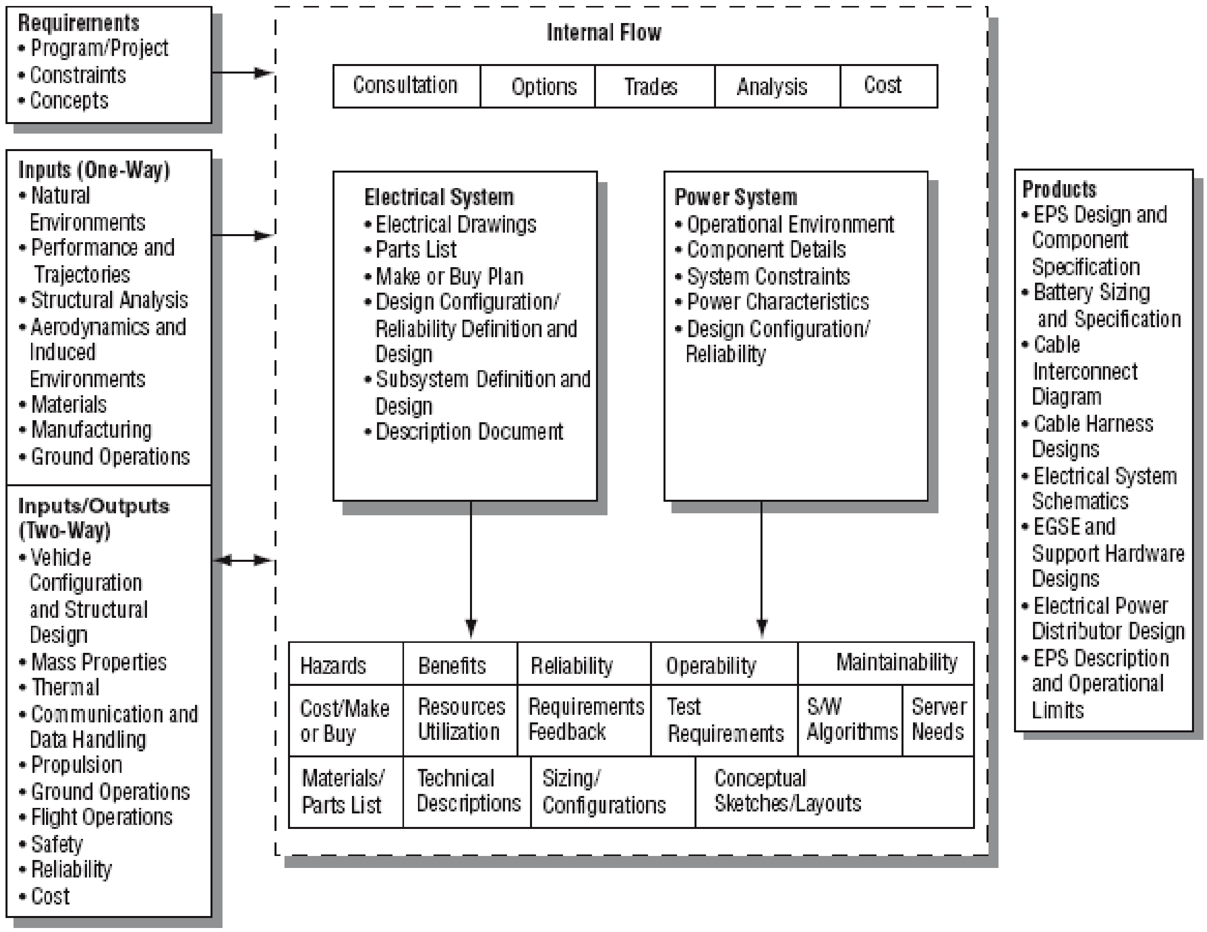


Figure 66. Inputs, Tasks and Outputs of a Typical Power System
[Humphries et. al., 1999]

3. Interfaces and System Design

a. Interfaces

As was stated in an earlier section, designing for and managing interfaces is one of the keys to successful space products. The process starts with requirements that are derived to minimize the number and complexity of the interfaces and their functions. In order to accomplish the requirements definition activity, we must first determine what interfaces are. Most have no problem in thinking of hardware/software type interfaces that include structure, mechanisms, electrical, and fluids, but interface management is much larger than these. In fact, just to properly manage the hardware/software interfaces requires additional types of interfaces that must be properly managed. These interfaces take the forms of information, models, organizations, etc. and require the same rigor and control as the hardware interfaces. They too must be designed to minimize the number and complexity of the interfaces and interactions that are required to satisfy their functions efficiently. All interfaces must be under a strict verification approach and a very stringent configuration control. The success of a project depends on the efficient selection and design of the total set of interfaces as a fundamental part of a system. We don't want to end up as the following cartoon shows (Figure 67), but want to end up as a uniform successful operating, coupled system.

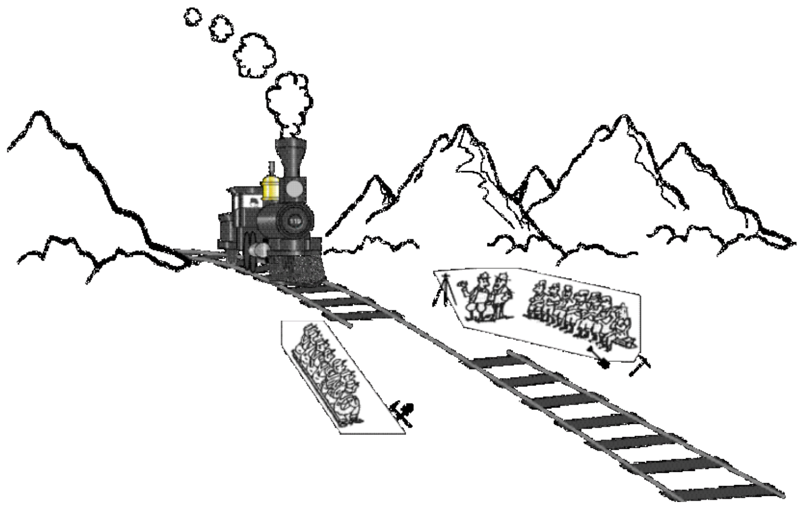


Figure 67. Example of Poor Interface Management

Figure 68 shows some of the interfaces between a flight computer and other onboard and ground systems. It is illustrative of the many interfaces among space systems, ground systems, and crew. It is obvious that these interfaces are not only electronic etc. but are very human driven. This means that managing of interfaces not only includes the hardware and software but all the people involved, greatly complicating the management task. Designing for the human/machine interfaces is in all probability the most complex task. Since so much of modern technology is driven by computers that require human interfaces, this becomes one of the key design drivers. In summary, designing, building, verifying and configuration control of interfaces is one of the major tasks the project manager and technical integrator faces and project success depends on its execution.

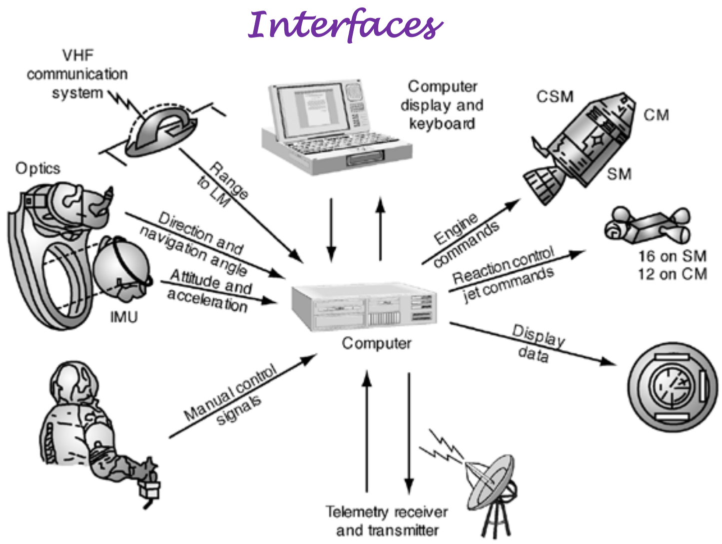


Figure 68. Typical Spacecraft Interfaces with Ground Systems

b. Rebalancing the System

When we upgrade the design of a subsystem we cannot just hand it back to the system and move on. The results of the subsystem design iteration must be integrated into the system. This reintegration in general will uncover additional interactions as the subsystem interfaces with and interacts with all the other subsystems that make up the composite system. When this is accomplished we find that the subsystem and the system do not act as they did before the changes. In other words there are no small changes. As was illustrated on the previous Figure 47, these interactions cause the system to have to be rebalanced and can result in changes to the derived requirements and/or fine tuning of each of the subsystems in order to reach an acceptable compromise to the system characteristics. This iterative process of rebalancing the system is a major task that requires the special attention of the project manager and the technical integrator.

D. Lifecycle Activities Following Detail Design Phase

1. Materials and Manufacturing

Materials selection, materials characterization, and manufacturing are central aspects of project development and require great attention of both the program/project managers and engineering to ensure process control, quality, schedule and cost goals. The level of material characterization heavily influences the selection of materials. We ultimately must select materials by considering the operational requirements (environments, natural and induced) and the engineering properties of the candidate materials. Typical requirements include, but are not limited to, application, operational environment transient or steady-state, static or dynamic loads, temperature, chemistry, contamination, life expectancy, and induced and natural environments. After we understand them, then we must match the requirements with particular engineering properties of the candidate materials which may include

- Mechanical properties (strength, toughness, thermal expansion etc.)
- Chemical properties (corrosion, flammability, toxicity etc.)
- Physical properties (density, specific heat, thermal expansion etc.)
- Compatibility with manufacturing methods (heat treating, tempering, surface treatment, joining)
- Compatibility with other materials
- Compatibility with test and inspection processes
- Availability
- Cost

In most cases, we must relate the candidate materials to each other by using combinations of the resulting properties, For example, when dealing with launch vehicle design, strength-to-weight ratios of candidate materials become extremely important because of the inherent need for lightweight, high-strength materials. Figure 69 illustrates the basic roles of materials and manufacturing.

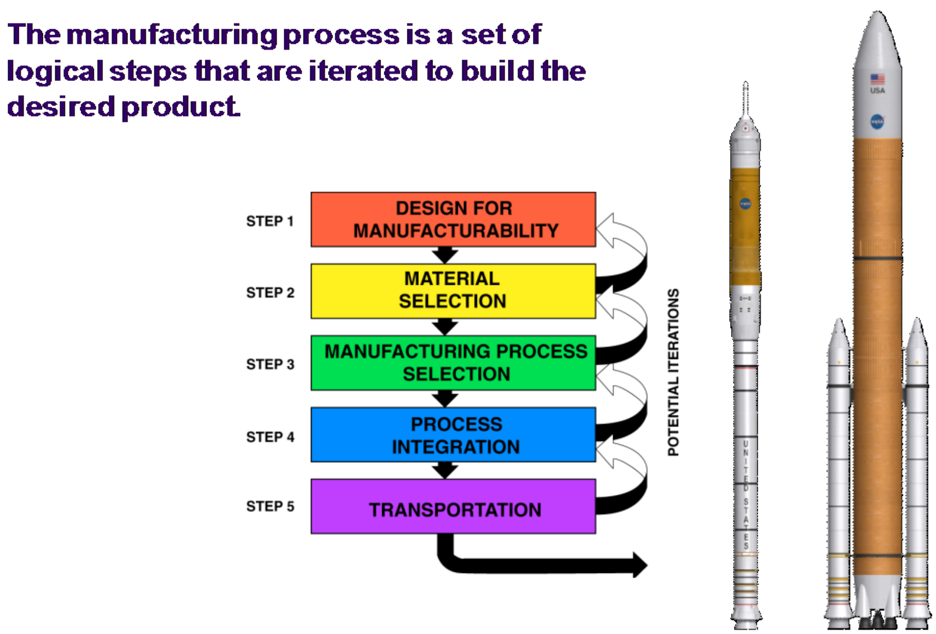


Figure 69. The Roles of Materials and Manufacturing
[SLaTS Course - Materials & Manufacturing, 2010]

Figure 70 illustrates the basic process for materials and manufacturing showing that it is a building block approach that starts with a literature search and proceeds to material characterization, material selection, manufacturing process selection and manufacturing. The manufacturing process and the built hardware then must be verified through test and analysis that it can meet the operational requirements under all predicted natural and induced environments. Material selection, manufacturing and verification are essential tasks that project managers must understand and manage.. The role of verification operations is discussed next.

Materials and manufacturing engineers make decisions and develop procedures that take the vehicle from the design stage to actual flight hardware.

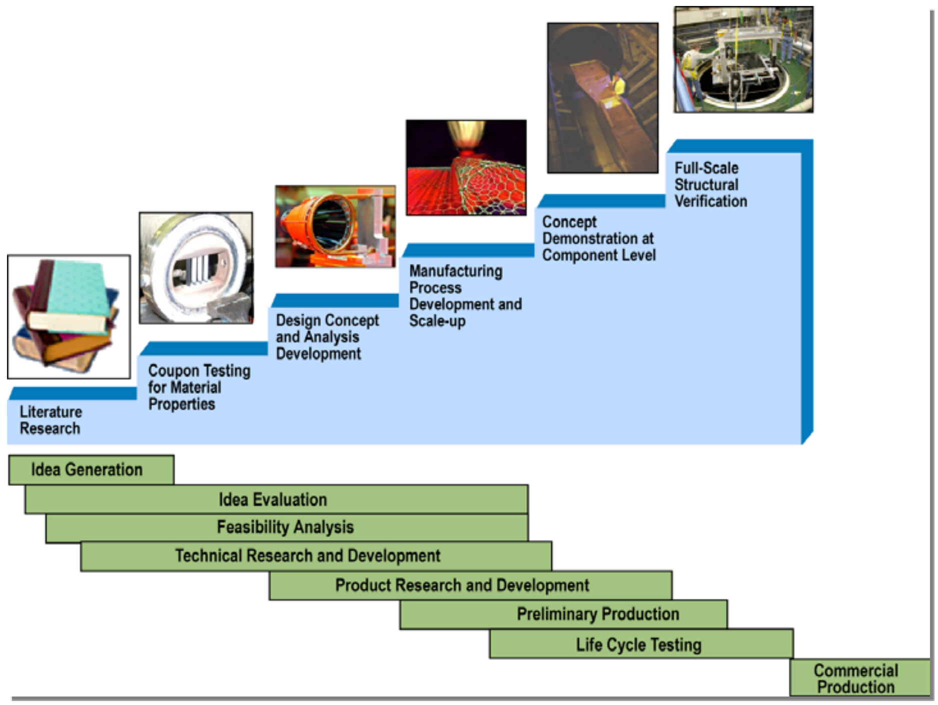


Figure 70. Process in Materials and Manufacturing
[SLaTS Course - Materials & Manufacturing, 2010]

2. Verification & Validation (V&V)

Verification and validation are a fundamental part of technical integration that must start with concept development and continue throughout the program in some form or level. We can achieve verification through test, analysis, demonstration, inspection, or similarity engineering, using these methods individually or in combination. Verification is the process whereby we demonstrate that a system can meet its specified requirements. Verification is always a major cost item, as well as an influence on other key system attributes such as weight and power. We verify design at the component, the subsystem, and the system levels. As a result, the systems engineering team must develop a top level verification plan with the support of all the design function engineers. A general set of definitions for the V&V function is:

- Verification – Proof, by examination of objective evidence, that the product complies with specifications. Verification is performed to ensure the product complies with requirements and may be determined by test, analysis, demonstration, inspection, similarity or a combination of these.

- Validation – Proof, by examination of objective evidence, that the product accomplishes the intended purpose. Validation is performed to ensure that the product is ready for a particular use, function, or mission and may be determined by test, analysis, demonstration, or a combination of these.

- Acceptance – A process performed to ensure all articles and materials meet the specified program/project quality requirements as documented and released through the approved program configuration management plan. This includes the closure of all applicable nonconformance reports and approval of all deviations and waivers.

- Accreditation – The official certification indicating that a model or simulation is acceptable for use for a specific purpose.

- Certification – (a) A written guarantee that a system or component complies with its specified requirements and is acceptable for operational use. (b) The formal written act whereby a responsible official attests to the satisfactory accomplishment of specified activities and authorizes the specified hardware/software, procedures, facilities and/or personnel for program usage.

Figure 71 illustrates an alternate way of looking at verification and validation showing that we start with what the user needs and what we build, then show that we built it right (verification) and that we built the right thing (validation). With this we verify requirements and validate expectations.

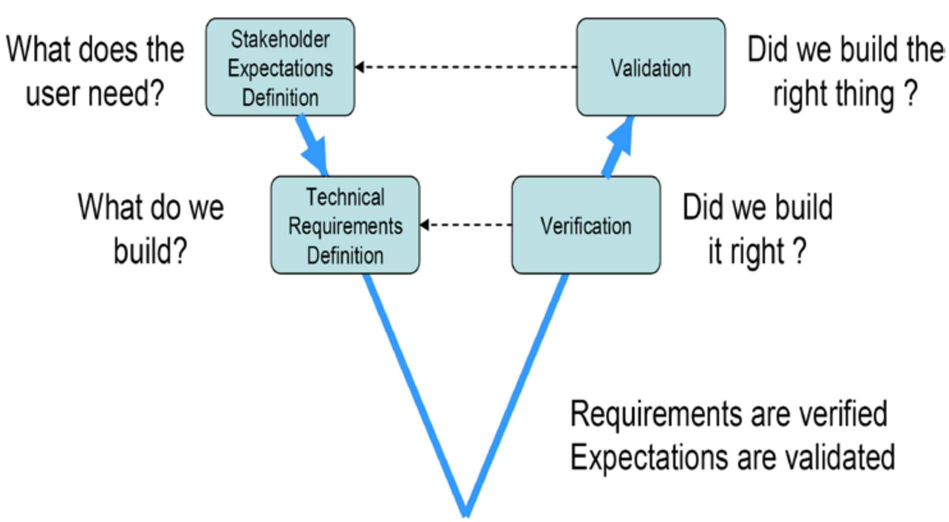


Figure 71. The Vee Diagram for Verification

Figure 72 is intended to show the process starting with requirements and then building the verification/validation objectives and plans. These use analysis, test and simulations to mitigate the risks associated with the product. Since test is one of the major cost drivers of verification the right hand side of the chart emphasizes the test objectives, events, test requirements and test procedures.

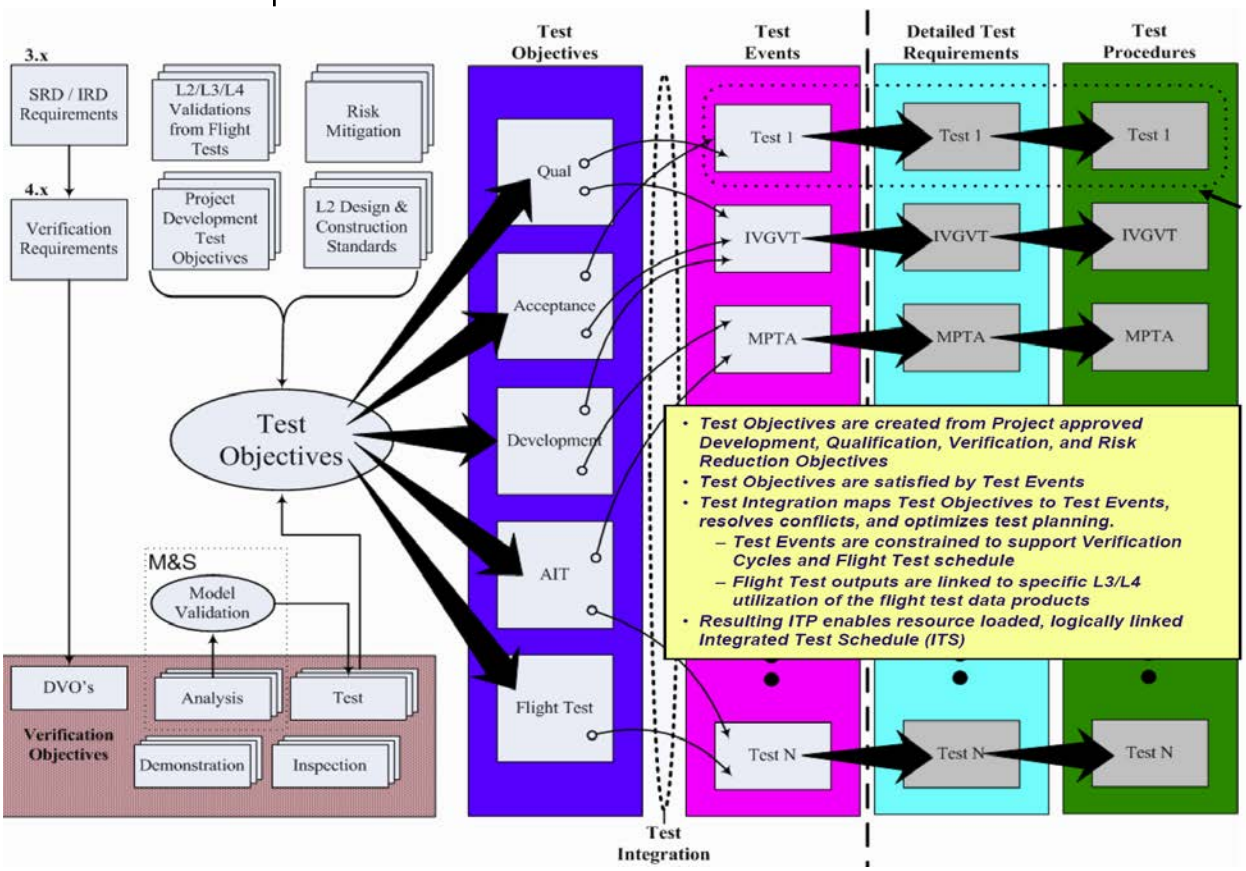


Figure 72. Verification Process Flow
[SLaTS Course - Verification and Validation, 2010]

The following defines the type of tests we do and what their objectives are.

1. Development Tests: Provide confidence in design
- Verify new technologies
- Assess environments
- Determine performance
- Anchor models
- Establish sensitivities, uncertainties and margins
- Develop manufacturing processes
- Uncover unknowns

Development tests are conducted throughout the design cycle of a project and are used to get basic information about the characteristics of the system, so that the design incorporates these characteristics and can handle the situations induced. Development tests include wind tunnel testing, scale model dynamic testing, thermal testing, materials testing, component vibration testing, acoustical testing, full scale testing of engines and other elements, etc. and are fundamental in understanding the systems. Component vibration tests and thermal vacuum tests uncover design flaws that can be corrected before final design is completed.

2. Qualification Tests: Flight-type hardware is verified to perform in severe conditions (3σ) to demonstrate margins

- Elements, subsystems, components, …
- Hydraulics, pneumatics, mechanisms, …
- Vibration and acoustics
- Thermal vacuum
- Hardware simulation labs
- Materials characterization

Qualification tests are generally of flight type or flight hardware that are tested to at least 3 sigma levels of the environments with the component carrying out certain flight type functions. Minor changes are easily made after these tests and if changes are required, the tests are generally repeated.

3. Certification Tests: Provide confidence that hardware is ready to go into production

- Verify system performance, durability
- Verify manufacturing and assembly processes
  - -- Workmanship
  - -- Manufacturing instructions
- Line replaceable unit process

Certification tests are usually for things like liquid propulsion system engines that can be ground tested under flight-like conditions using both flight hardware and flight operational procedures. For example certification of the Space Shuttle Main Engines required that two identical engines be tested under flight profiles and operational procedures for 20,000 seconds each. Some of the major problems experienced during certification testing will require either hardware changes and a repeat of the certification testing or flying the system under waivers and operational constraints.

4. Process Assurance Tests: Provide confidence in continued acceptability of production process by sampling and testing from production runs

- Solid rocket motor firings
- Pyrotechnics tests

Process assurance tests are generally for solid rocket motors and pyrotechnic devices. Hardware like this is either very costly or is destroyed in the tests so lifecycle testing is not appropriate. The test program usually consists of a few (say 5) motors or devices before flight. During the operational program, a motor or device is periodically pulled from the manufacturing line and tested to ensure that the build process is still meeting requirements.

5. Acceptance Tests: Demonstrate end item will meet design and performance requirements for a specified mission

- Components and systems
- Green run tests
- Wet flight readiness test

Acceptance tests are usually of avionics and mechanisms where each unit is tested when it comes off the production line. The tests are not of full flight duration and are at reduced environments. This testing is to eliminate manufacturing or infant mortality flaws. Flight liquid propulsion engines are tested in this manner using a short duration hot firing of the engine. At various times in space programs the engines attached to flight stages are ground hot fired for short durations to understand the interaction of the engines with the main propulsion systems.

6. Systems Integration and Verification Tests: Demonstrate that integrated system's physical, functional, and informational interface requirements are satisfied.
Integrated tests are of many types to either validate analytical models or to obtain basic natural and induced environments. The following is a partial list of integrated tests for launch vehicles.

- Integrated ground vibration (dynamic) tests to validate dynamic models
- Main propulsion tests to understand the integration of engines with the main propulsion system elements and software
- Wind tunnel testing for static aerodynamic characteristics, aeroelastic testing to determine elastic body effects on aerodynamics, acoustical testing to determine aeroacoustic environments, aerothermal testing to determine heating environments, etc.

7. Flight Readiness Firing: Demonstrate integrated system will meet key on-pad requirements during engine firing. We can do Flight Readiness Firings on the launch pad, of short duration burn time, of launch systems with liquid propulsion systems. This is done to check out the MPS after any major changes made from prior configurations.

8. Other tests:

- Development test flights
- Post-flight tests

Flight test programs of launch vehicles are typically the first two or three flights that are heavily instrumented in order to determine combined environments and interactions that are that are not possible to accomplish in the previously discussed tests. Flight testing has uncovered many major problems that were not found during prior tests. Post-flight tests are done to assess the condition of recovered hardware after its use.

Implementation of verification and validation is a very costly part of any space program or project. For example a liquid engine that is started in space requires a highly specialized test facility that simulates the vacuum conditions of space. The Ares I launch vehicle was to use for its second stage a derivative engine of the original J-2, named J-2X. It required an in-space start, and a major facility to develop this capability. A new facility is being constructed that can accomplish this task. Figure 73 is a pictorial of the facility with some of its characteristics.

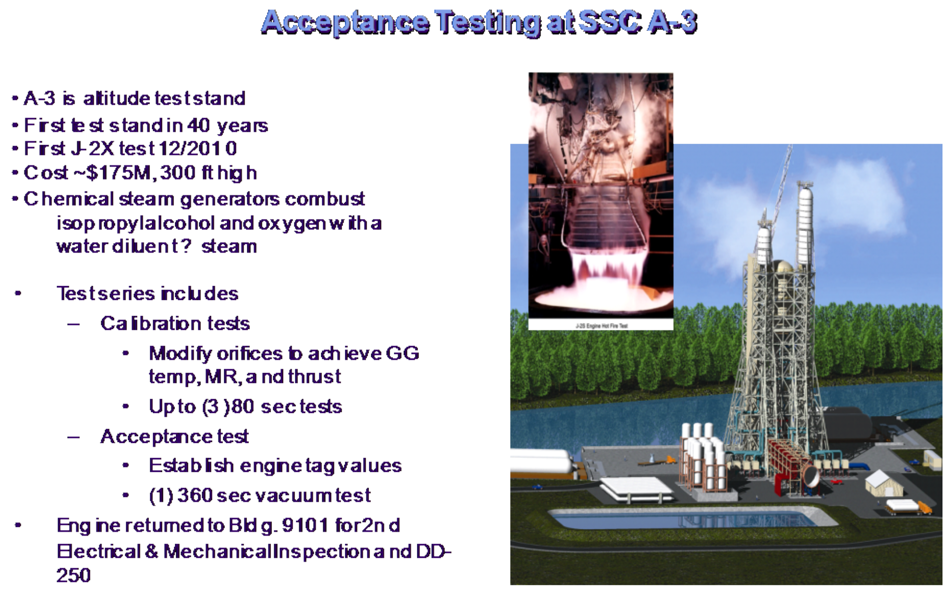


Figure 73. Vacuum Liquid Engine Test Facility
[SLaTS Course - Verification and Validation, 2010]

Many other special facilities are needed for verification and validation of any space system and consist of facilities for structural testing, thermal testing, aerodynamic testing, software testing, vibration testing etc. Prioritizing and managing these systems is one of the major tasks of a project manager.

In summary, what does all this verification and validation process mean to a project manager? The following list provides a quick summary of the requirements.

- All analytical models/tools must be validated
- All design and operational data must be validated
- Components must have development, qualification and acceptance testing
- System/subsystem capability must be verified
- Solid motors must have development and process assurance testing
- Liquid engines must be certified
- All interfaces must be verified
- Software must be validated and certified
- Final checkout must be confirmed
- Integrated system must be verified and validated

Successful completion of the process means that the product meets requirements and will operate to meet its intended purpose.

Not only must V&V verify and validate the final product but must verify and validate the manufacturing process, the transportation system, operational system, etc. The V&V process requires the best management skills a project manager can muster and is one of the key secrets to program success.

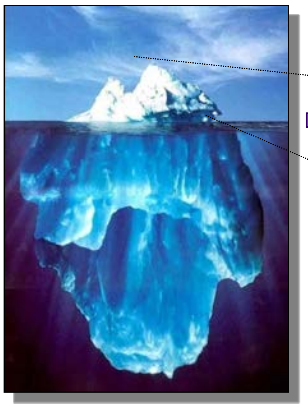
3. Operations

Options for field and flight operations concepts are nearly unlimited. Choosing a practical, cost-effective approach is crucial to achieving economical operations of our space systems. Quoting from the Space Launch and Transportation System (SLaTS) book: [Larsen 2008] **"**A simple plea: as operators assigned to a launch vehicle design team we must contribute to the design process from the beginning. We need to provide serious engineering input in the form of prior analysis and we need to bring our planning tools. The process steps in this section describe the first iteration in the concept exploration and early concept definition phases. Similarly, the engineering design team must bring the operations specialist to the table early, to avoid designing a vehicle that is inherently difficult to operate and support. The team can't wait for their concept to be "assessed," quite probably misunderstood, and subsequently dismissed. They may be seeking only commitment for a vehicle design, but the ultimate decision makers, somewhere down the road, must make a larger commitment than just a vehicle. They must commit to space transportation architecture, complete with facilities and support infrastructure, an operational workforce, and a logistic supply chain."

KSC did an Access to Space study in 1994 that identified drivers in the direct and indirect cost of space operations for a launch vehicle that is shown on Figure 74. The major cost is not in the visible, direct tasks but is in the indirect hidden tasks. As this study shows, the launch vehicle must be designed along with the operational system to reduce these hidden costs. Accomplishing this is a major management task.

STS Recurring Cost Perspective

- "Direct" (Most Visible) Work Drives Massive (and Least Visible) Technical & Administrative Support Infrastructure
- Example: Direct Unplanned Repair Activity Drives Ops Support Infra, Logistics, Sustaining Engineering, SR&QA and Flight Certification



STS Budget "Pyramid"
(FY 1994 Access to Space Study)

Generic Operations Function	Total $M FY94	*Total (%)*	
Elem. Receipt & Accept.	1.4	*0.0%*	~10%
Landing/Recovery	19.6	*0.6%*	
Veh Assy & Integ	27.1	*0.8%*	
Launch	51.5	*1.5%*	
Offline Payload/Crew	75.9	*2.3%*	
Turnaround	112.3	*3.3%*	
Vehicle Depot Maint.	237.5	*7.1%*	~20%
Traffic/Flight Control	199.4	*5.9%*	
Operations Support Infra	318.6	*9.5%*	
Concept-Uniq Logistics	842.7	*25.1%*	~70%
STS Ops Plan'g & Mgmnt	1477.4	*43.9%*	
Total ($M FY94)	**3363.4**	***100.0%***	
Percent	**100.0%**		

Reference: KSC

Figure 74. The Cost of Operations by Operational Functions
[Kennedy Space Center, 1994]

Figure 75, another KSC study result, shows the manpower spent on operations for the Space Shuttle, categorized by vehicle subsystems. Notice that thermal protection systems and propulsion systems and their fluids are the big drivers in manpower. To reduce cost of operations the design effort must focus on the areas of high manpower. It is a very complex management task that balances the systems between performance, operations, cost, and other -ilities.

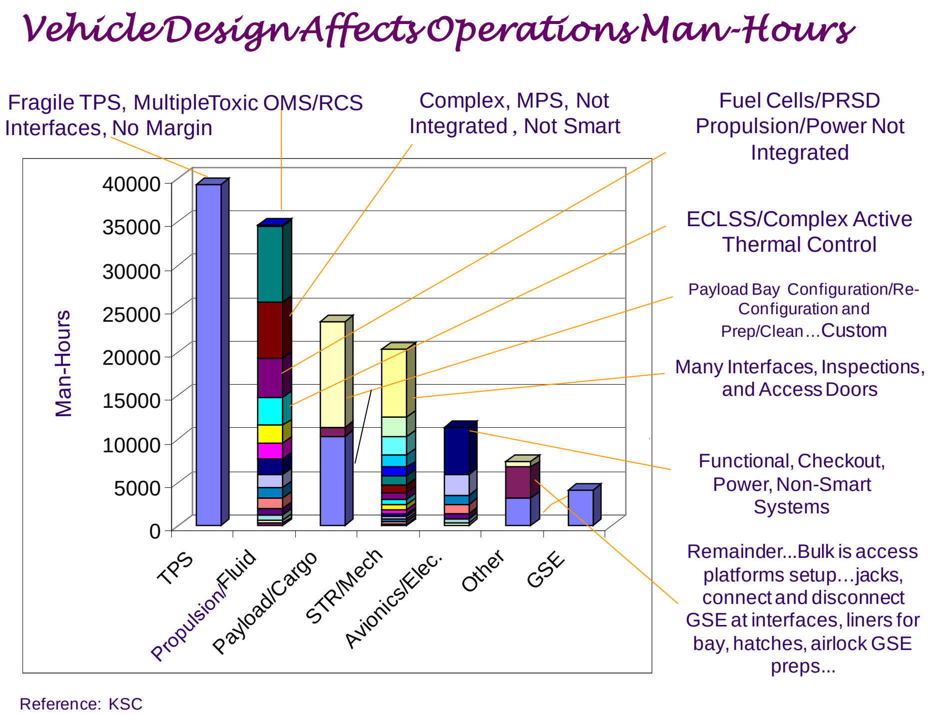


Figure 75. Space Shuttle Operational Man-hours by Subsystems
[Kennedy Space Center, 1994]

Transportation of hardware from the manufacturing facilities to the launch facilities is another operational cost driver. Figure 76 is a pictorial of the various types of transportation used today.

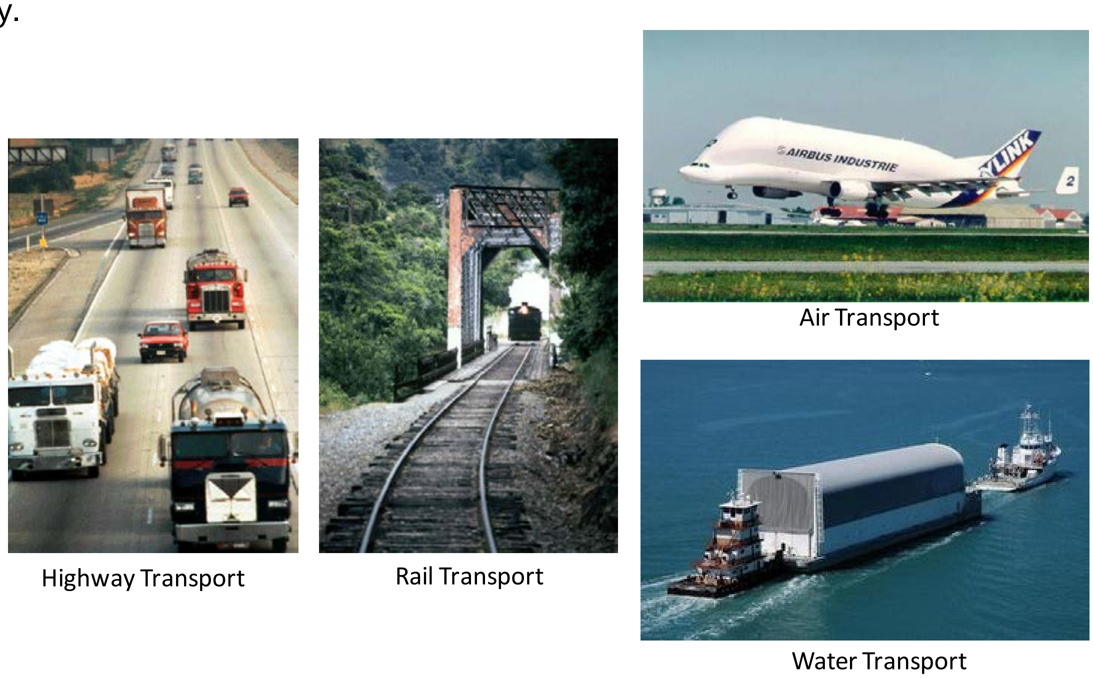


Figure 76. Modes of Transportation for Space Systems
[SLaTS Course - Operations, 2010]

E. Decision Making

We have looked at many aspects of designing space systems and space launch vehicles. Putting all these pieces together requires making decisions that best balance the system technically and programmatically. This is a foreboding task that we must attack in a logical and effective manner. As was stated earlier in the report we accomplish the decision making task by:

- Understanding and quantifying uncertainties and sensitivities
- Determining and allocating margins
- Defining, managing and mitigating risks.
- Balancing the system (Making the key decisions)

1. Understanding and Quantifying Uncertainties and Sensitivities

In the design of complex systems there are always top level requirements, constraints, ground rules, and assumptions that set the stage for accomplishing the design. It is the designer's challenge to figure out how to strike balance among them. Included in the art of design is knowing how to apply sensitivities, uncertainties, and margins to achieve the best balanced design with confidence. As we have emphasized throughout this report, sensitivity analysis is a key tool to achieve the best balance among the design's attributes. This is accomplished by assessing the changes in the attributes that result from changes in the design variables. This produces the sensitivity factors (partial derivatives). It enables the designer to iteratively converge the design and involves the application of analysis, test, and simulations. Uncertainty pertains to random variations in design input variables at all levels and the corresponding random variations in the design attributes (outputs). These variations are about mean values and are determined via historical data bases, tests, and expert opinions. Margin pertains to the difference between some measure of capability and some measure of demand. Understanding uncertainties and application of adequate margins throughout the various stages of the project provide the necessary confidence in the design of systems with high power densities. The uncertainties can be categorized as epistemic and aleatory uncertainties. The details of how to handle the different types of uncertainties is left to the reader and is a course within itself.

High performance systems have high sensitivities and uncertainties which complicates the design. If a comparison is made between the design efficiency (power/pound) of a rocket stage and an airplane, the rocket stage is about two orders of magnitude higher in design efficiency. If compared to an automobile, the rocket stage is about three orders of magnitude higher.

Sensitivities and uncertainties have to be determined and assessed through all stages of the design process. This requires attention to design detail to assess the best design decisions and potential for reducing uncertainty. In fact, uncertainty can in some cases be reduced by reducing sensitivities. A major concern in design is determining the uncertainties in the output variables in terms of uncertainties in the input variables. Some of the methods used to assess these uncertainties are root-sum-square (RSS) and Monte Carlo simulations.

In the early phases of design it is important to ensure adequate margins are provided to assure headroom for unknown effects of sensitivities and uncertainties. As the design activity proceeds every effort must be made to understand sensitivities to achieve the best balanced design and to reduce uncertainty to reduce risk and provide design confidence.

The following is an overview of uncertainty in rocket engine and structural design. In rocket engine design, high uncertainty results in high development cost. Figure 77, see reference [Havskjold, 2004], illustrates the effect of uncertainty on high cost. The figure on the left is the number of rework cycles (corrective actions) as a function of technical uncertainty factor for various subsystems. As the uncertainty increases the number of rework cycles increases. The uncertainty is a result of high static and dynamic flow induced loads, thermal transients and gradients, high pump speeds, welds, etc. In the figure on the right is the cost versus the number of years in the development. It can be seen that 73% of the development cost is a result of corrective actions (test-fail-fix). In the development of the SSME there were 38 significant incidents (failures of hardware during test) that cost over $30 million per incident.

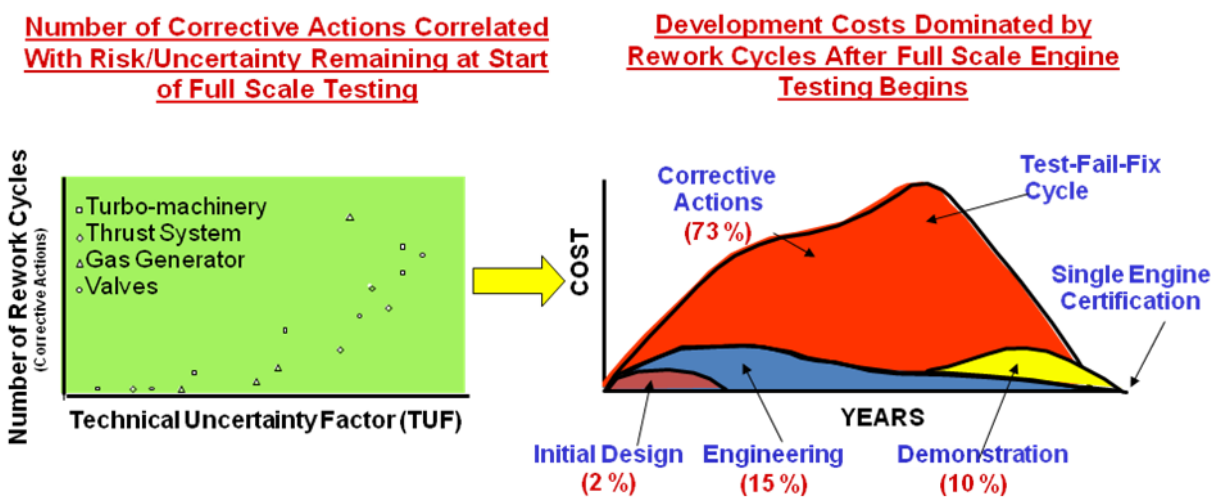


Figure 77. Technical Uncertainty Leads to High Cost
[Havskjold, 2004]

Having the experience shown in Figure 77, what can be learned to improve the effects of uncertainty? Shown in Figure 78 is an indication of how reducing uncertainty and improving processes can reduce development cost.

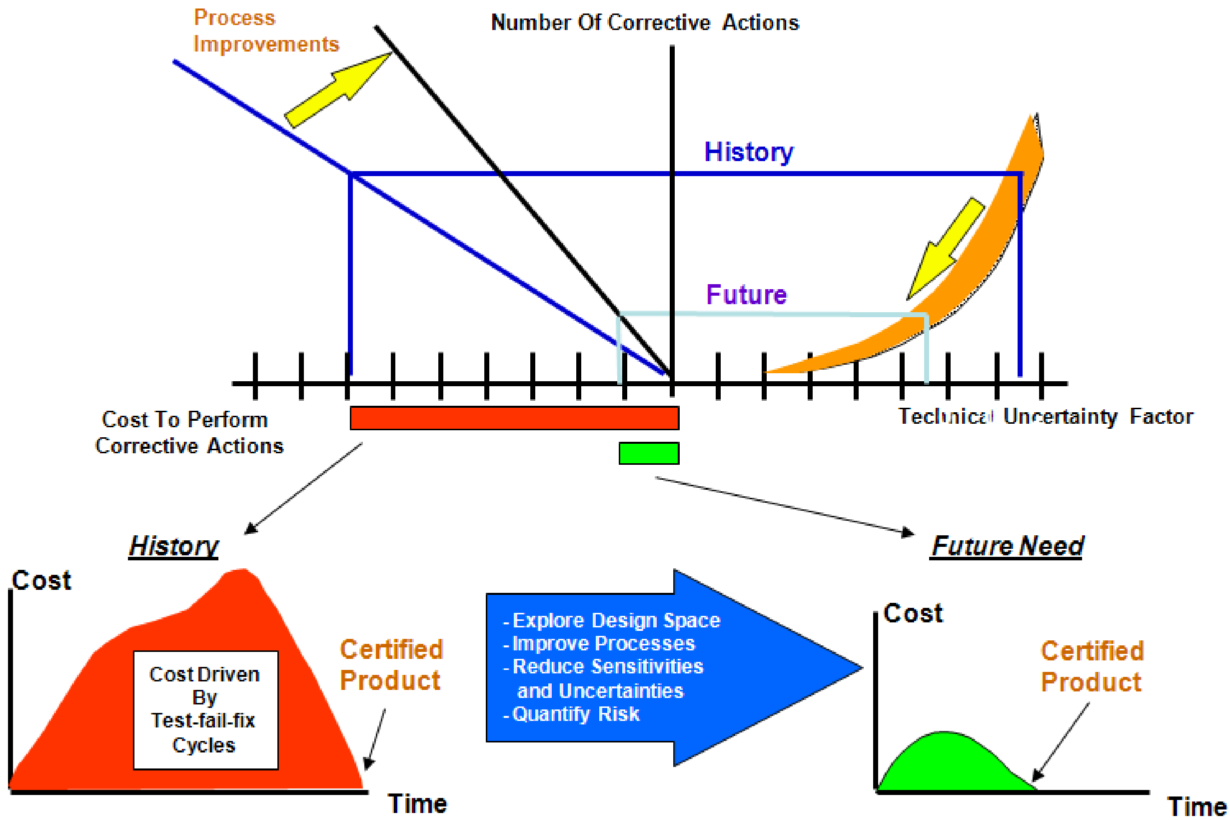


Figure 78. Combined Effect of Low Uncertainty and Improved Process to Reduce Cost
[Havskjold, 2004]

Figure 78 indicates that as the uncertainty is reduced the number of corrective actions can be reduced and by process improvements the cost of corrective actions can be improved. The net effect will be reduced cost to achieve a certified engine. Uncertainty can be reduced by lowering the static and dynamic flow induced loads, e.g. decrease chamber pressure and open up flow areas. In addition, uncertainty can be reduced by reducing pump speeds, improved definition of environments, etc. Process improvements can be achieved by minimizing welds, application of friction stir welding, bonding by high isostatic pressing, reduced part count, etc. Overall by building on our experience base and by implementing new design technologies as shown in Figure 79, significant cost reductions can be expected in the future.

Reliability & Standardization

RS-68 Designed for Producibility

	RS-68	SSME
• Unique Part Count	~181	2204
• Welds	~115	1077
• Touch labor (hours)	8,000	171,000

- 10:1 parts reduction
- Advanced manufacturing enabled by design
  - – Casting, not welding
  - – No special coatings
- Twice the Thrust 650,000 lbf @ Sea Level

Figure 79. Engine Reliability and Standardization
[Wood, 2002]

Uncertainty in structural design is illustrated in Figure 80.

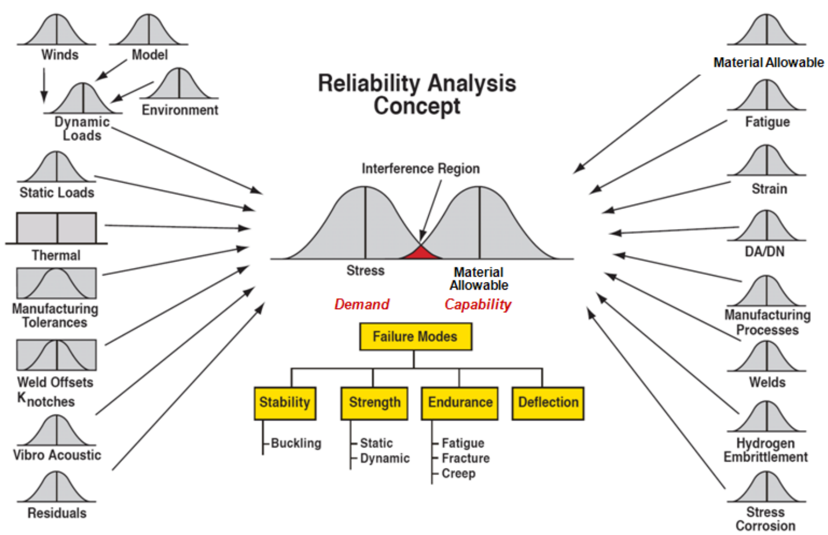


Figure 80. Uncertainty in Structural Design

In the middle of the figure are the probability density functions (PDF) of the working stress and the material allowable. In the region where there is overlap, failures will occur. In this example, the design has considered all the failure modes and the failure mode of concern is the strength. The variability in the material allowable can come from the random variations as characterized by the right-hand PDF's and for the stress the variability can come from the random variations associated with the PDF's in the left hand column. Knowing the associated PDF's, the reliability of the design can be determined. In the example shown, the design would be unacceptable because of the size of the interference region. Various changes can be made. The mean stress can be reduced by reducing the load or changing geometry. The uncertainty could be reduced by restricting the uncertainty in the load, changing tolerances, improving welding, etc. The material properties can be improved by changing the material to one that has a higher allowable or one with less uncertainty or both.

Sensitivity and uncertainty play important roles in the design of complex systems where there are high power densities. Sensitivities provide insights regarding developing the best balanced design and also aid in reducing uncertainties. Knowing the uncertainty provides a means for assessing risk and provides confidence in the design. Understanding past experiences (lessons learned) and applying new design tools provide visions toward design improvements to reduce cost in the future.

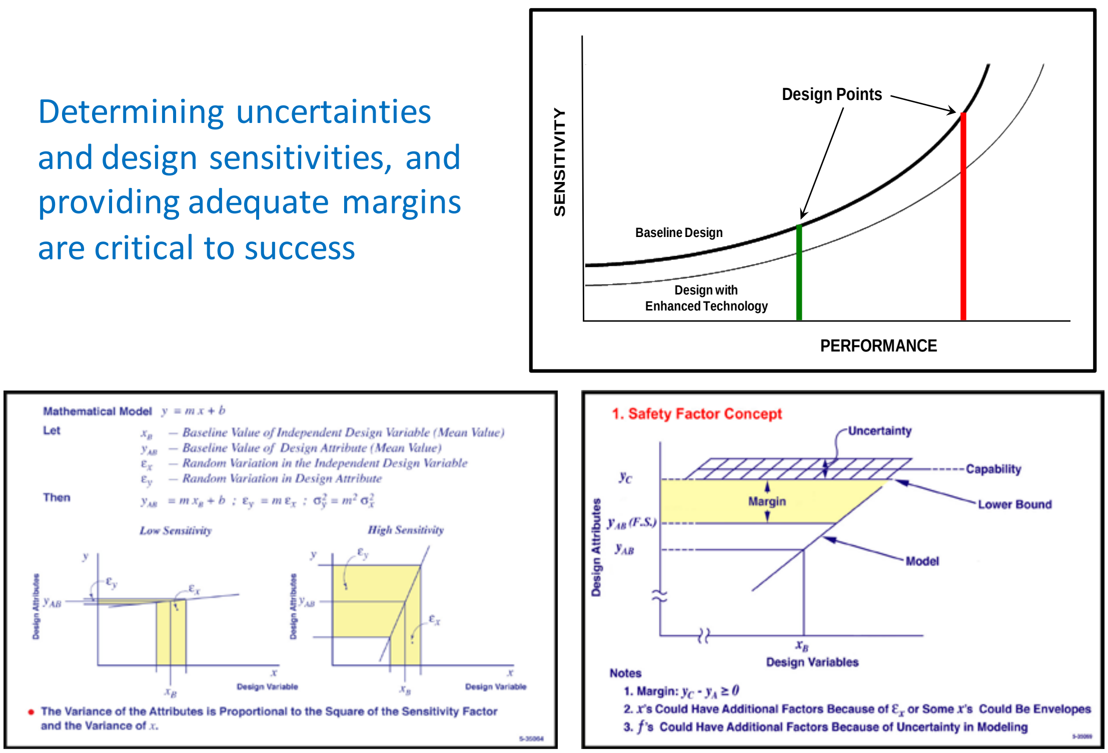


Figure 81. Principles of Uncertainties and Sensitivities
[SLaTS Course - Sensitivities Uncertainties & Margins, 2010]

At the lower left of Figure 81 is a graphic representation of the sensitivity of two different systems to the same parameter uncertainty. In one case the output is a very small change in the response due to the variation of the parameter while in the other the response change is very large. The ideal system would be the first curve; however, many times it is not possible to get the ideal insensitive system which then means that we must understand the system in more detail. The right hand bottom figure is how we apply margin to the three sigma responses to cover additional things that can't be known and to cover growth as a system matures.

A principle we learned many years ago in working the numerous SSME problems and failures says; the higher the performance requirements the greater the system of the system to any parameter uncertainties. All of this high power density and high efficiency comes with a price as illustrated on Figure 80 top right corner of chart. This is a generic curve which represents a number of different physical systems. For example the structural SN Curve for fatigue is the inverse of this curve. A plot of vehicle dry weight versus dry weight margin will basically trace this generic curve. What this means then is that as we move out on the performance curve, our design, verification and operations efforts go up non-linearly with the increase in performance requirements. It means that great attention must be used to design, build, verify and operate these high performance systems.

2. Determining and Allocating Margins

Understanding the uncertainties and sensitivities forms the basis for adding margins to the system during the process of conception and design to account for the unpredictability of the system. For example we know that the mass of system grows during design as a function of the maturity of the technologies used in the system. Mass margin has a mass growth allowance allocation and depletion plan, a mass margin and depletion plan and a program mass reserve. This is managed throughout the project life cycle (Figure 82). Each of NASA's projects defines the areas that it will assign and manage margins for, then specifies a process for that management. For example, margins are identified for mass, performance, power, software, thermal protection, clearance, controllability, communications, launch availability, operability, etc. A plan comparable to the one for mass management must be developed for all areas where margins are to be assigned. Typical plans for previous projects are available in NASA documentation.

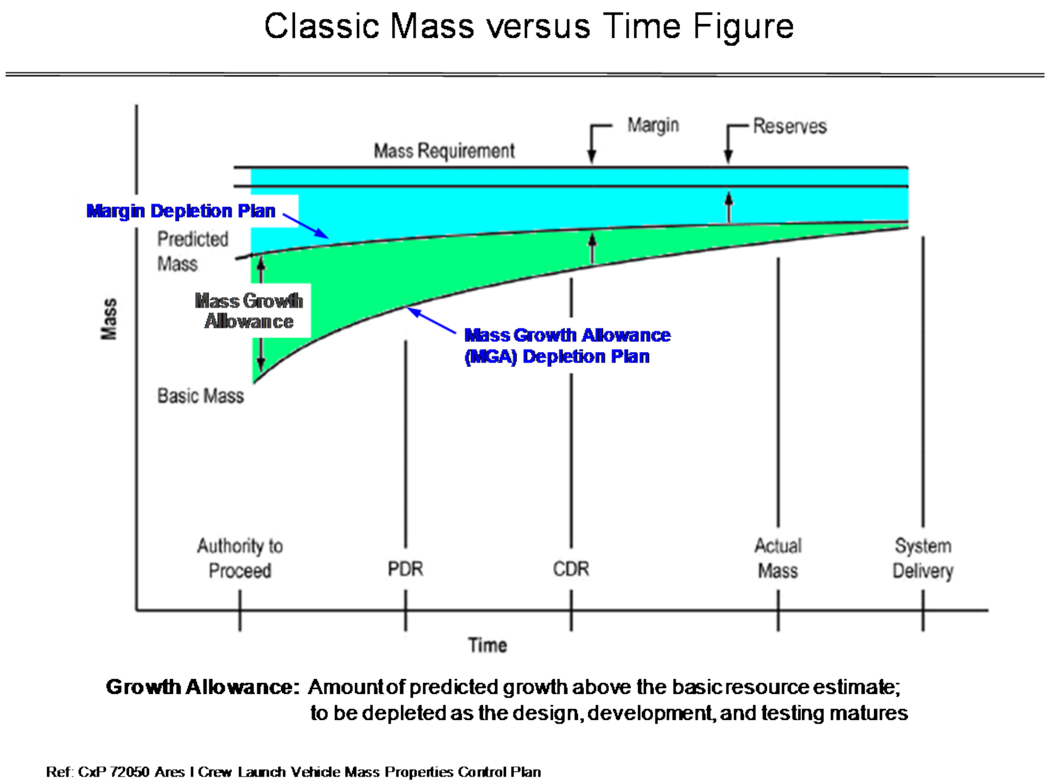


Figure 82. Typical Mass Margin Management Aproach for Total Lifecycle
[SLaTS Course - Margins, 2010]

3. Defining, Managing and Mitigating Risks

Risk pertains to situations where there are undesirable and uncertain events that could be detrimental or have adverse consequences. In the development of space hardware, risk is concerned with the likelihood of occurrence of undesirable end states and the severity of resulting consequences.

Throughout the lifecycle process, various risks of the system must be assessed, understood, and managed. These risks are both technical and programmatic. The decision making process dictates that we make these decisions based on the total risks of the system. Technical risks deal with potential failure modes and their probability of occurring as well as the severity of the consequences of the failure. Programmatic risks of cost and schedule are similar in their approach. Technical risks have an impact on the programmatic risks and vice-versa, as illustrated in Figure 83.

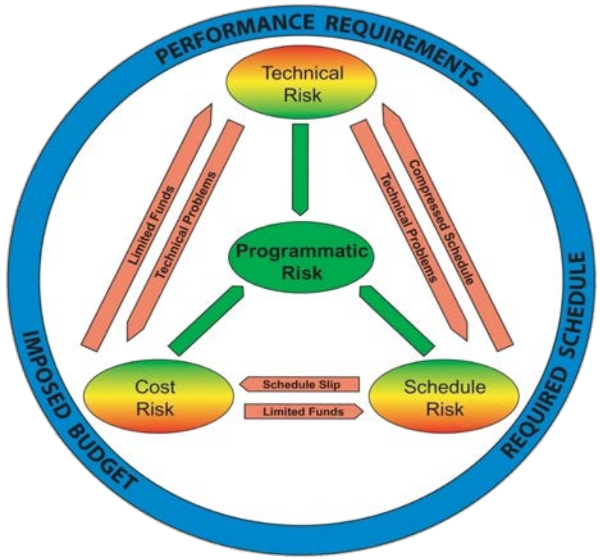


Figure 83. Relationships Among Risk Categories
[SLaTS Course - Risk Assessment, 2010]

Risk assessment and management guides the design through all stages of the design process. In the end, it provides confidence in the final design. Risk *assessment* pertains to the process of identifying and modeling potential risk scenarios, determining the associated probablility of a occurrence, the severity of the consequences, and actions required to reduce the risk to an acceptable level. Risk *management* is a process concerned with identifying, analyzing, planning, tracking, and controlling risk.

Concerns relating to risk occur during all stages of the design process. They pertain to all categories of risk-- technical , cost, and schedule. The main focuses of technical risk are *safety* (personnel, assets, and environmental) and *performance* (requirements, operations, and supportability). After a risk assessment is accepted it is usually prioritized by a project review team. The application of risk assessment and management enables the project to focus on the most pressing issues. The project's goal is to balance all risk categories and bring them to a level as low as practically possible.

Figure 84 provides a risk assessment taxonomy. It can be seen that there are two major methods associated with risk assessment. One method deals with risk matrix assessment and the other deals with probabilistic risk assessment (PRA).

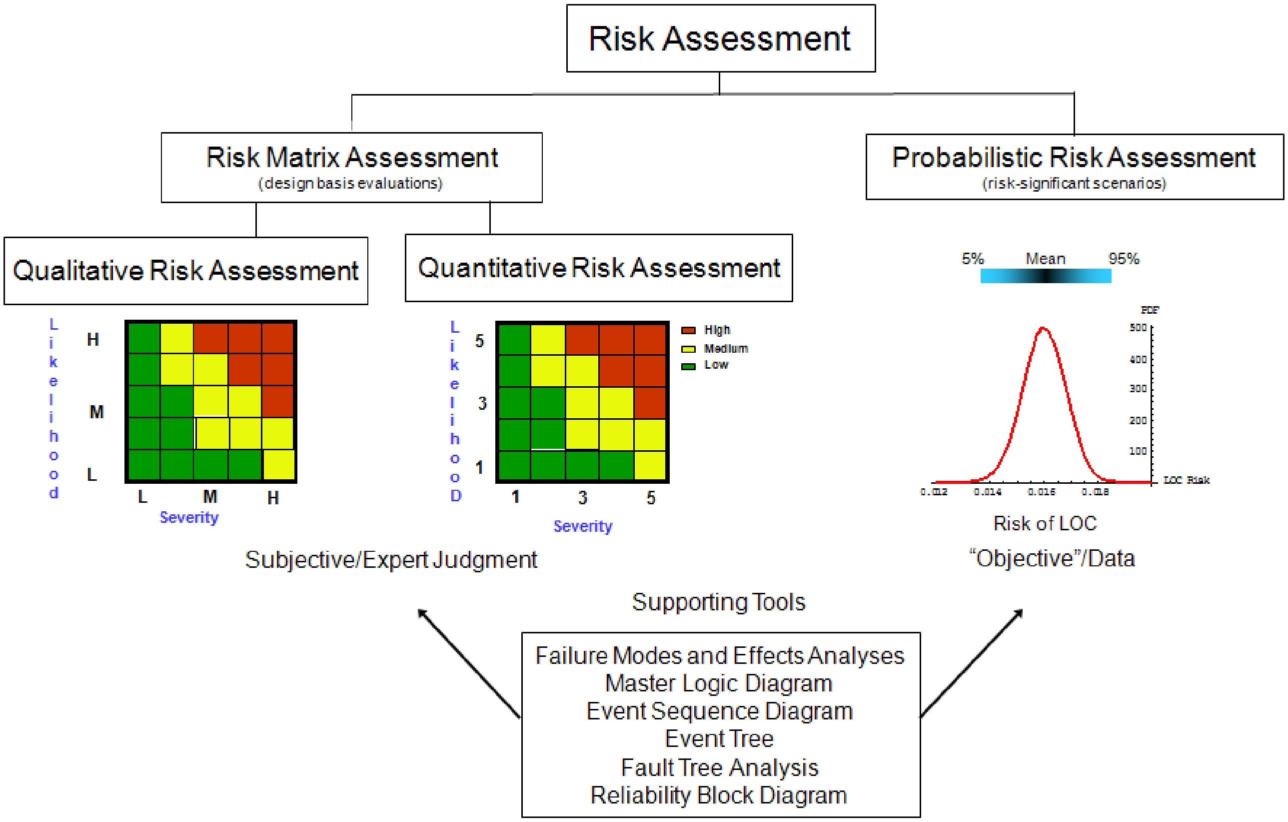


Figure 84. Risk Assessment Taxonomy
[SLaTS Course - Risk Assessment, 2010]

The risk matrix method usually applies to project levels 3, 4, and 5. The main purpose is to determine and assess undesirable events associated with technical (safety and performance), cost, and schedule and includes participation of engineering and S&MA. They determine the likelihood of an undesirable event and the corresponding severity. The risk assessment then goes to the project team where the priorities are determined. This methodology was established in the mid to late 1970's and continues to be refined to accommodate various applications.

PRA is a method that is usually applied to project levels 2, 3, and 4. This method is usually applied to assess events that have a low probability of occurrence, but with enormous consequences, for instance: loss of crew, loss of vehicle, or loss of mission. One of the distinguishing features of PRA is the determination of uncertainty associated with the risk level. As can be seen from the figure the results are represented by a probability density distribution. This methodology was developed in the early 1970's to assess risk associated with nuclear reactors.

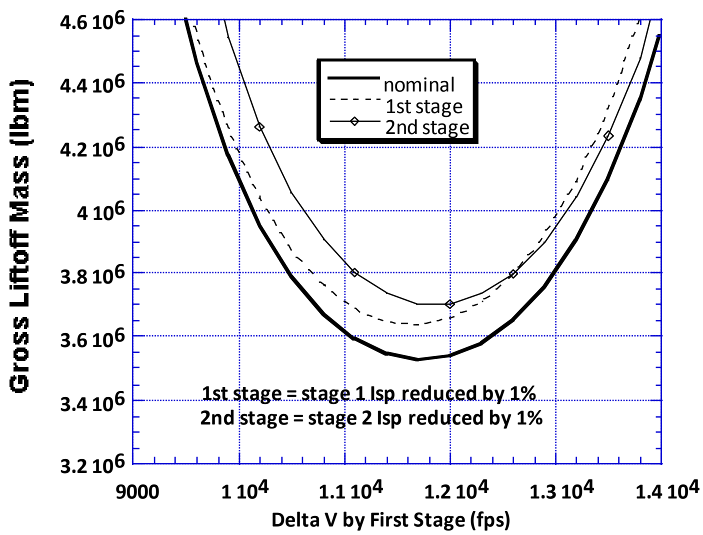
4. Balancing the System (Making the Key Decisions)

Using the results of the uncertainties, sensitivities, margins, and risks the system must be balanced in a best possible manner in respect to performance, the -ilities, cost and schedule. This involves making decisions as to the best balance throughout the process.

Early decisions determine the characteristics that the system will have throughout its life cycle. How we make these decisions is obviously one of the keys to product success and is therefore a key function of project managers. For example, shown of Figure 85 is the gross liftoff weight of the vehicle as a function of the delta-v split between the first and second stage of a 2-stage launch vehicle. If weight alone is the driving metric then the delta-v choice would be that which gives minimum weight; however, other considerations such as commonality might shift the decision away from the minimum weight solution. The number of factors such as the delta-v split are complex and become the inputs to the decision making process. Decisions usually have impacts on the system that are realized throughout the project life cycle. The decisions to select the parallel burn Shuttle configuration and to have it satisfy the launch requirements of both the Air Force and NASA had major impacts on the project, effected throughout the life cycle. Air Force cross range and payload size drove the Orbiter configuration determining the payload bay size and the Orbiter wing configuration. This wing configuration in all probability affected the reentry thermal protection system design (tiles).

Factors in Decision Making

Example: 2-Stage Sensitivity to Staging Point and Isp



•The sweet spot of Delta V split is shown in the plot of GLOW vs Delta V Split showing the large sensitivity of GLOW to the Ist stage Delta V .

•Other factors that must be a part of the decision of what Delta V split is best:

- •Commonality
- •Reliability
- •Cost
- •Schedule
- •Manufacturability
- •Power Density

Figure 85. Launch Vehicle Gross Liftoff Weight Versus Delta V Split Between First and Second Stage

[SLaTS Course - Trajectories, 2010]

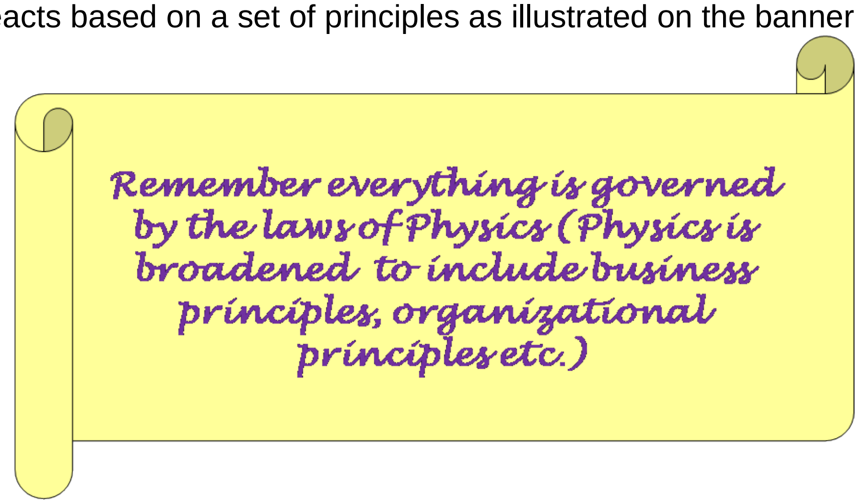
The one-and-a-half stage configuration, the lift/drag characteristics and the volume geometry drove the SSME to have high power density and high thrust/weight which caused many of the fracture, fatigue and manufacturing problems. As a result, to solve many of these problems, the SSME had at least three block changes that included the two duct manifold, the large throat powerhead, and the alternate high pressure turbopumps. The parallel burn configuration created a system of four bodies connected by struts that created a set of complex load paths, very complex dynamics, complex aerodynamic flow paths and complex thermal protection systems. The vehicle was very sensitive to small changes that led to very detailed and complex analysis and test cycles. As the system matured, several element block configuration changes were required to meet the performance and reliability requirements. For example the External Tank had two block changes, the Lightweight Tank and the Super Lightweight Tank, that together increased Shuttle performance 17,000 pounds. All of this resulted in comprehensive and costly V&V and operational impacts. Numerous problems occurred that were major impacts to the program, including

- Overpressure effects
- STS-1 aerodynamic anomaly
- 38 major SSME ground test failures
- Orbiter tile problems
- Challenger
- Columbia

Another example of major decision impacts was increasing the SSME thrust to 104% to reduce payload losses on Space Shuttle. This created

- Numerous fracture, fatigue, wear, loads and instability problems
- Many engine ground test failures
- Strict hardware inspection process
- Stringent clean room requirements
- 50% fleet leader rule (Factor of two on time in two ground test engines of comparable part being flown)
- Block hardware changes throughout the life cycle

A fact that we need to constantly remind ourselves in making decisions is that everything reacts based on a set of principles as illustrated on the banner below.



Decisions can not violate the laws of physics. Figure 86 is an excerpt from The Cartoon Guide to Physics by Larry Gonick and Art Huffman showing examples of some principles of physics.

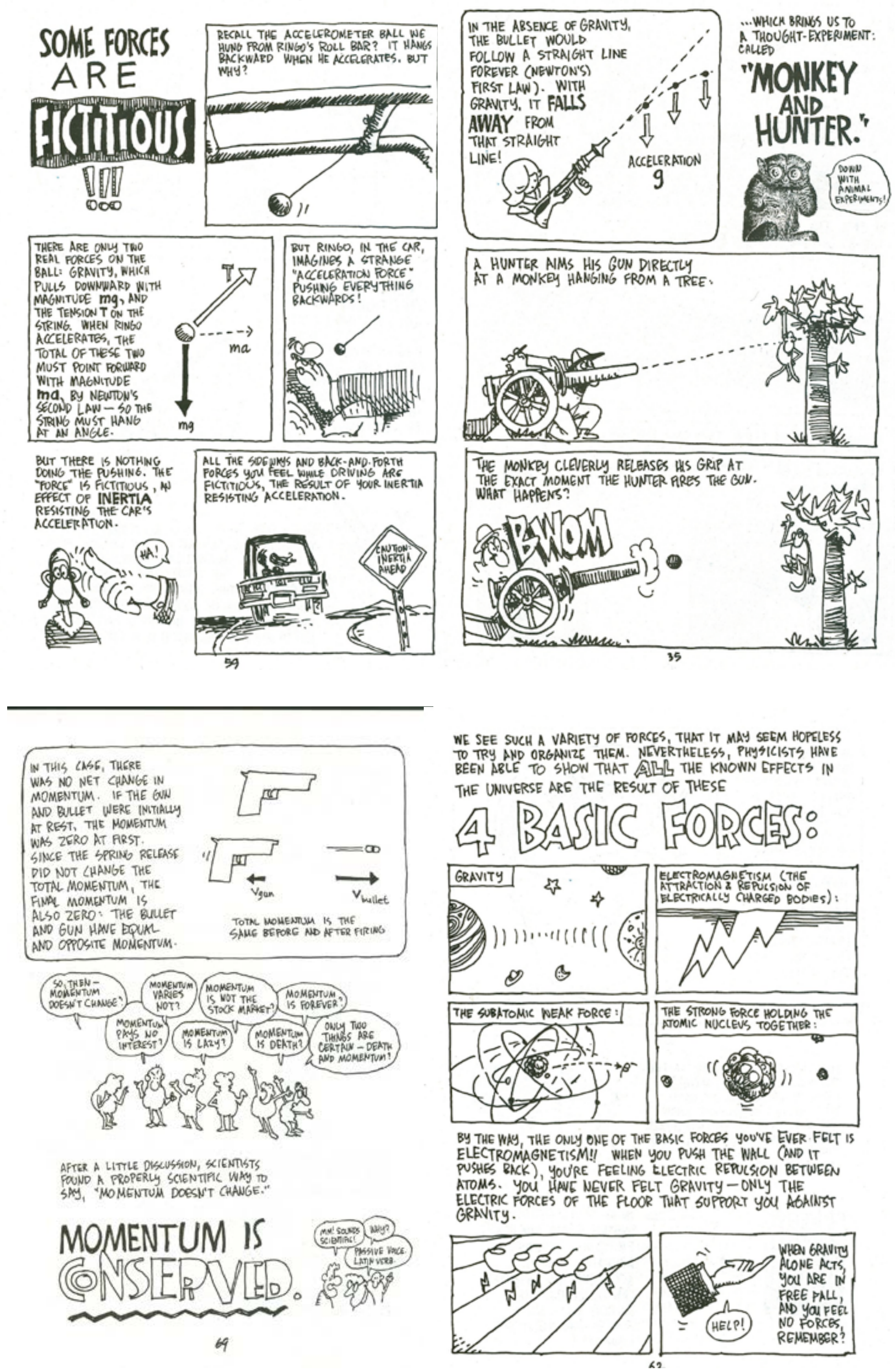


Figure 86. Physics Rules, It is the God of Design
[Gonick & Huffman, 2005]

There are many decision process tools that can used to apply the above considerations into an assessment to aid in making decisions. Most of them develop a set of metrics of the system that include performance, programmatics, etc. These are then weighted and comparisons of different options are made. None of these approaches are absolute but they can be good guides to aid the decision making process. In the end it is basically the human judgment that makes the final decisions, either as an individual or as a team consensus.

F. Managing the Design

Nothing in a project continues to run smoothly. We are constantly faced with a set of problems that must be managed or decisions made concerning them. Figure 87 is the arc of creativity used in problem solving. The process starts by breaking the problem apart and putting it back together so that you can take a fresh look at the interfaces. When this is accomplished the problem is reformulated and fruitful analogies are visualized. The sensitivities are then searched to determine positive order of magnitude changes that could be made, always being alert to serendipitous solutions.

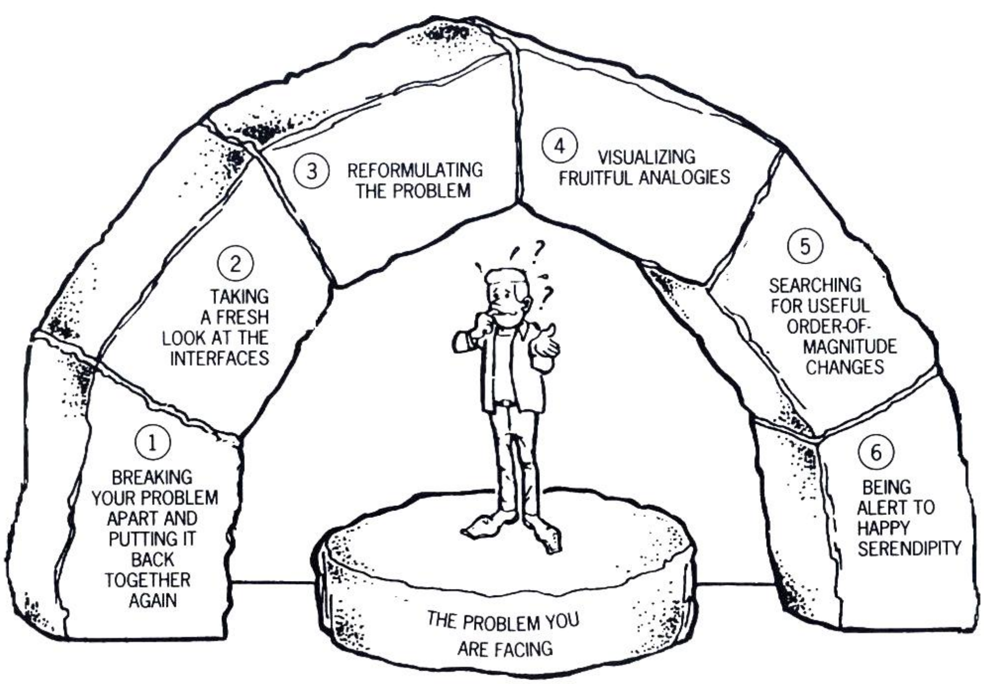


Figure 87. How We Manage the Problem We are Facing in a Project. Management of the Design, The Arc of Creativity
[We have misplaced this reference]

It is clear that managing the evolution of design is a very multifaceted and intensive activity. There are technical, business, organizational and cultural aspects that must be actively addressed. Some of the focus areas related to Engineering the System include:

- Trades and Balancing
- Configuration Management
- Technical Performance Measures and Parameters
- Growth Allowances and Margins
- Verification
- Risks
- Integration

In working trades and balancing, management should ensure that

- All pertinent options are considered
- Options are assessed on basis of all attributes: performance, -ilities, cost, safety, sensitivities, risks and margins
- Options are chosen that provides best system balance for life cycle

Configuration management requires significant management attention to ensure consistency among the many concurrent activities. Areas that are under Configuration Management include:

- Requirements
- System / subsystems descriptions and attributes
- Drawings and specifications
- Project design data books

All evolution and changes of the controlled configurations requires much management effort and attention to detail.

Technical Performance Measures (TPMs) are critical and are key performance parameters monitored to assess how well design meets requirements as a part of the management process. They are:

- Key indicators used to confirm progress and identify deficiencies that might jeopardize meeting a system requirement
- Product drivers that can have a significant impact on safety, cost, schedule, risk, or technical performance
- Top level; a relatively small set
- Monitored by comparing the current actual achievement of the parameters with that anticipated at the current time and on future dates
- Reported at management reviews, along with their related margins

The remaining areas on the list have been previously addressed.

Not only must the manager deal with the physics of the problem and evolution of the design, but must deal with the role the organizations have in the project.

G. A Role of the Organization

Organizations play many key roles in the management of project integration. The first major task of the organization is to keep the vision and mission in constant definition and focus. As the old saying goes, the vision and mission set the sails and keep the system pointed in the right direction. Using the analogy of the fundamentals of space flight one can draw some of these management principles that the project manager and the organization need to apply to keep things on track. Figure 88 is an example from the GN&C aspects of flight. The end point on the curve represents the mission and part of the vision. While flying toward this point, disturbances occur which cause deviations of the system from the desired path. There is a navigation system that continuously tells the vehicle where it is in space, how fast it is going, and the direction it is pointed. The guidance system then takes that information and compares where it is versus where it should be. It is very costly to try and go back to the original path so the guidance system calculates a new path to the target. Then as the vehicle exits the atmosphere with its disturbances, the control system points the vehicle along the new path and maintains system stability while following the new guidance path to the target.

Any project as it moves through its life cycle will encounter many disturbances that knock it off course. These can be technical issues, cost, schedules, political changes, etc. The first principle then is not to try to get back on the old path, but to create a new path to the vision and mission. This retargeting is one of the main tasks of management that requires a navigation system to tell it where it is, a guidance system to retarget the path and a control system to keep the system stable and pointed in the right direction.

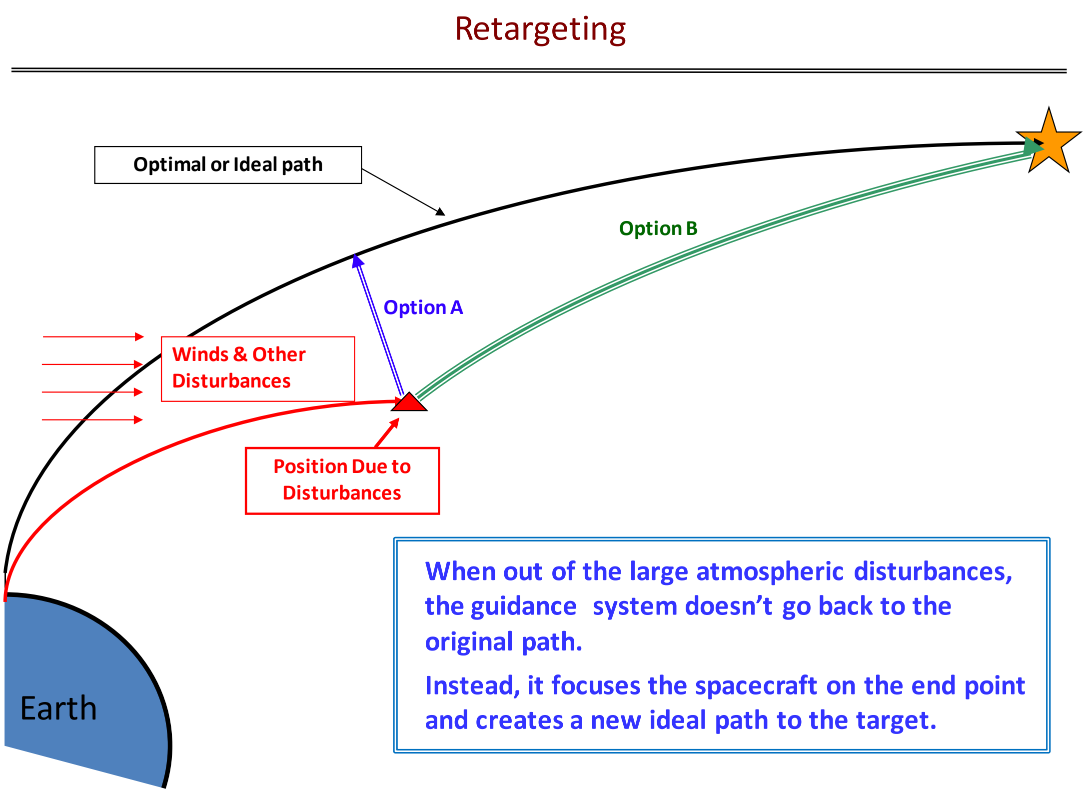


Figure 88. Space Vehicle Principles Applied to Organizations and Individuals

Many times however, due to large external factors or disturbances, retargeting is no longer possible and the mission must be aborted. In some cases politics will cancel the original mission. Figure 89 illustrates the effects of these type of changes. If the new target is within the characteristics of the system then the decision becomes whether you go for it or abort. In the case where the mission is canceled a new mission must be planned. There are many examples within NASA where programs were moving along and hardware being built when the program was canceled, or the program was canceled before the entire individual missions were accomplished. Examples include Apollo, X-33, fully reusable shuttle etc. When this happens there is much travail unless a new program is quickly inserted to take its place. If the program is canceled and no new mission is readily apparent then there is fear and anxiety. It is very important that a replacement vision and mission be established as soon as possible to alleviate the building of fears, anxiety and internal power plays.

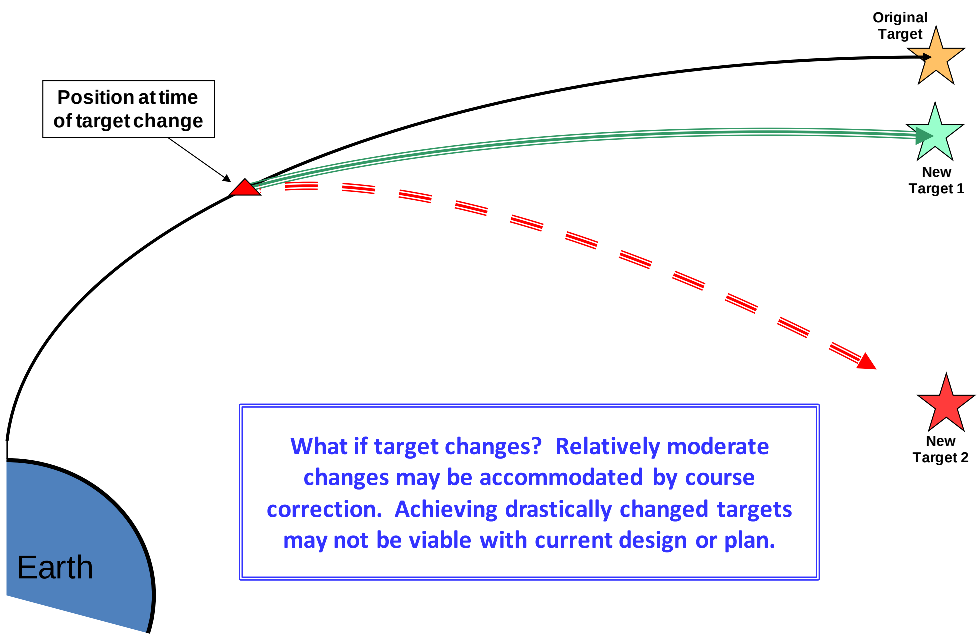


Figure 89. Target Changes and Potential Impacts

Figure 90 illustrates that even with a new vision and mission that there is a place between the places of the past and the future where there is fear and anxiety present. Once the new place is established there occur many rewards such as growth and fulfillment. It is mandatory that managers understand this place between the places. Many years in the past Dr. Paul Tournier addressed the subject in great detail. The following quotes are taken from his book by the title “A Place for You”.

- ❖ However, the law we discovered in regard to man’s place remains true: one must first have a place in order to be able to leave it. In the same way, one must first have a support in order to be able to jump. One cannot jump without a spring-board or some solid support from which to take-off. One must start from a strong support in order to make a successful jump-even to risk a jump at all.

- It is one of the laws of life that one stage successfully completed prepares the way for the next, while failure in one stage lays in advance a heavy handicap on the next.
- There is a place that must be left before we can find a new place and in between there is a place without a place, a place without support, a place which is not a place, since a true place is a support.
- In the middle of the way there is a zone of uncertainty in which the mind is divided between two contradictory suggestions.
- There is a past security to be lost before we find a new security. No security lasts, however solid, just or precious. For it is a law of evolution that tomorrow will not be the same as yesterday, and that there results from that difference the anxiety of today, since each moment is a middle zone between the past and the future.

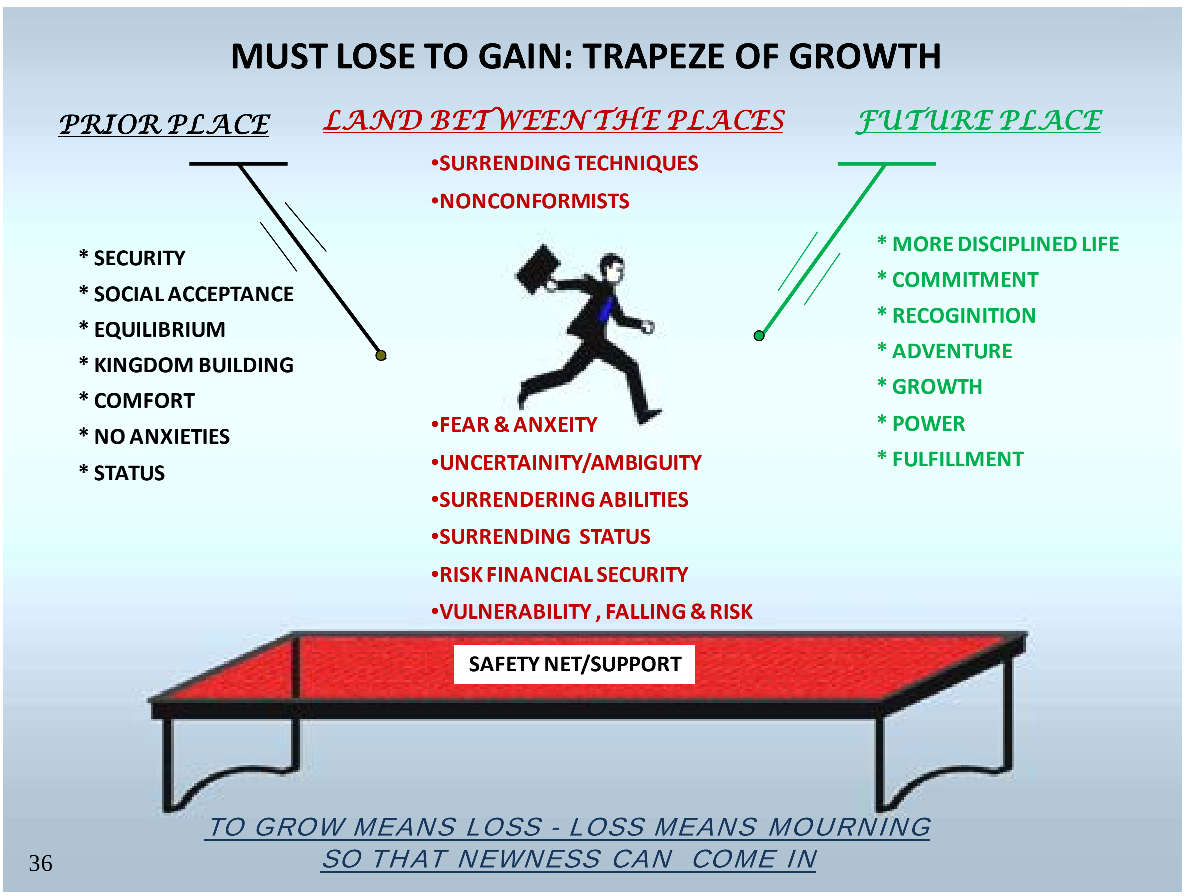


Figure 90. The Trapeze of Growth

The fundamental question is “How do we manage organizations to achieve project success?” The organization can be just as complex as Engineering the System and Technical Integration requiring near equal time and effort for each. As a result both have comparable roles in achieving project success. Robert Pool in *Beyond Engineering: How Society Shapes Technology* [Pool, 1997] says:

- ❖ No single person can comprehend the entire workings of, say, a Boeing 747.
- ❖ In truly complex systems, no amount of testing or experience will ever uncover all the possibilities, so decisions about risky technologies become a matter of how much uncertainty one is willing to put up with.
- ❖ The defining feature of complex systems is ***how its parts interact***. Furthermore, a complex technology generally demands a complex organization to develop, build, and operate it, and these complex organizations create yet more difficulties and uncertainty – organizational failures often underlie what at first seem to be failures of a technology.
- ❖ The safety of complex systems depends not just on their physical characteristics but also quite ***intimately*** on the ***people and organizations*** operating the systems.

The organization must therefore focus on its most important resource, *Its People Empowerment.* There must be organizational and communication simplicity. The use of teams such as IPT's if formed and managed correctly can aid organizational efficiency. The organization must have enough control to maintain coherence but not so much as to constrain innovation and creativity of its people. Again quoting from Poole's *Beyond Engineering*:

- ❖ Layered organizational structure, seems to be basic to the effectiveness of organization. …Some groups are bureaucratic and hierarchical, others professional and collegial, still others are emergency response. … Because of complexity, they are best decentralized; because of the tight coupling they are best centralized. …They emphasize constant communication –***talk-talk-talk*** far in excess of what would be thought useful in normal organizations. The purpose is simple, to avoid mistakes. … Poor communications and misunderstanding, often in the context of a strict chain of command, have played a prominent role in many technological disasters. … Besides communications, high-reliability organizations also emphasize ***active learning***, not simply the ***memorization of procedures***.

H. The Process for Achieving Excellence

At the request of the Director of Engineering at Marshall Space Flight Center we put together a short course on the process for achieving excellence in engineering. The approach that was used to derive the principles of engineering excellence is shown on Figure 91. The process began with a study of the major incidents experienced by the authors working for NASA. This study was used to develop root causes from technical, organizational and cultural considerations.

The study identified five top root causes that have led to major problems in NASA. They are:

1. Shifting from engineering "hands on" and "excellence" to "insight/oversight". Lack of ownership.
2. "Normalization of the deviances". Not questioning anomalies.
3. Lack of critical thinking. Over-reliance on procedures and computer codes.
4. Decentralization of authority.
5. Organizational and technical complexity.

Taking the incidents studied and the resulting root causes led to the development of an approach for achieving excellence in engineering. This approach may be divided into three elements as illustrated in Figure 91. First, *Technical Understanding and Execution*—it is basic that what we do in engineering must be technically correct. Second, *Partnership with the Project*—successful products require a positive, productive relationship between Engineering and the Project Office. Third, *Individual and Organizational Culture*—all activities are undergirded by the prevailing culture, which must foster the attitudes and behaviors necessary for success in producing and operating our complex systems. Figure 92 takes each of the three elements and expands them into their main components. These components are discussed in detail in a NASA CR yet to be published and are not repeated here.

Figure 91. The Process for Excellence in Projects

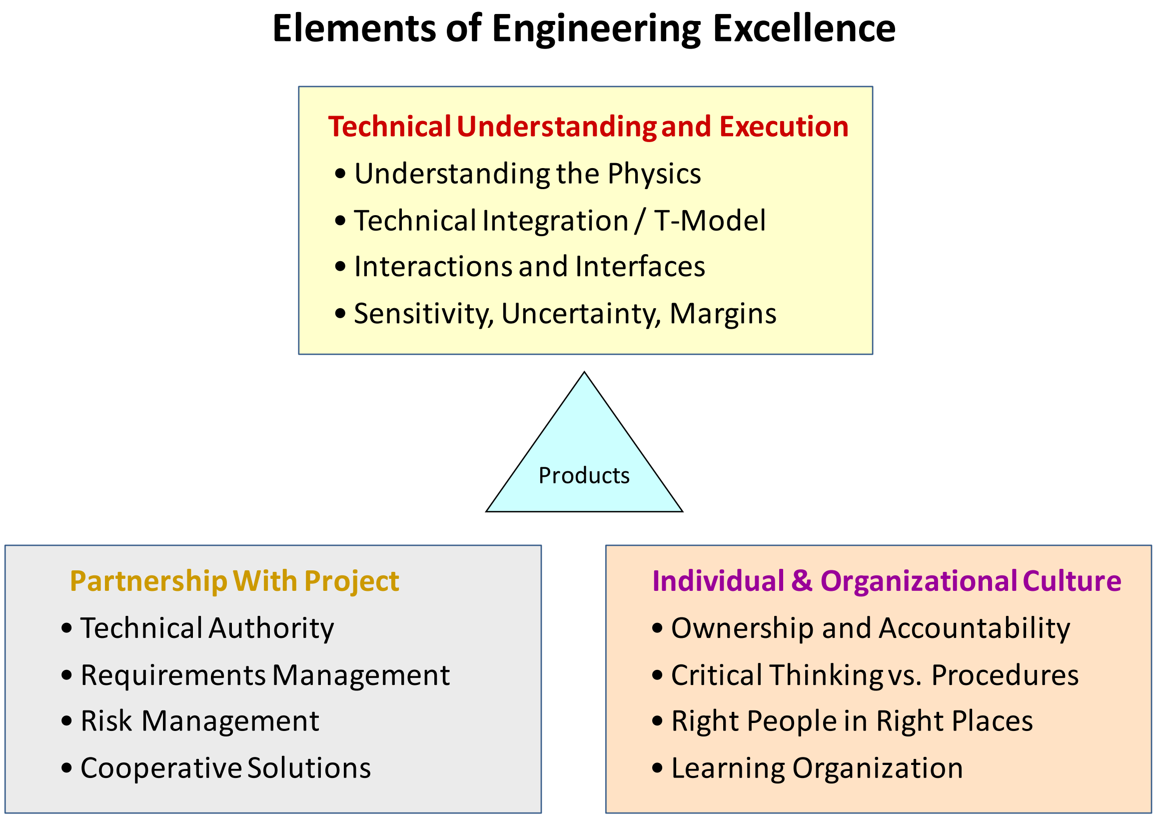


Figure 92. Elements of Engineering Excellence

V. Summary and Conclusion

The report has addressed Engineering the System and Technical Integration defining them as:

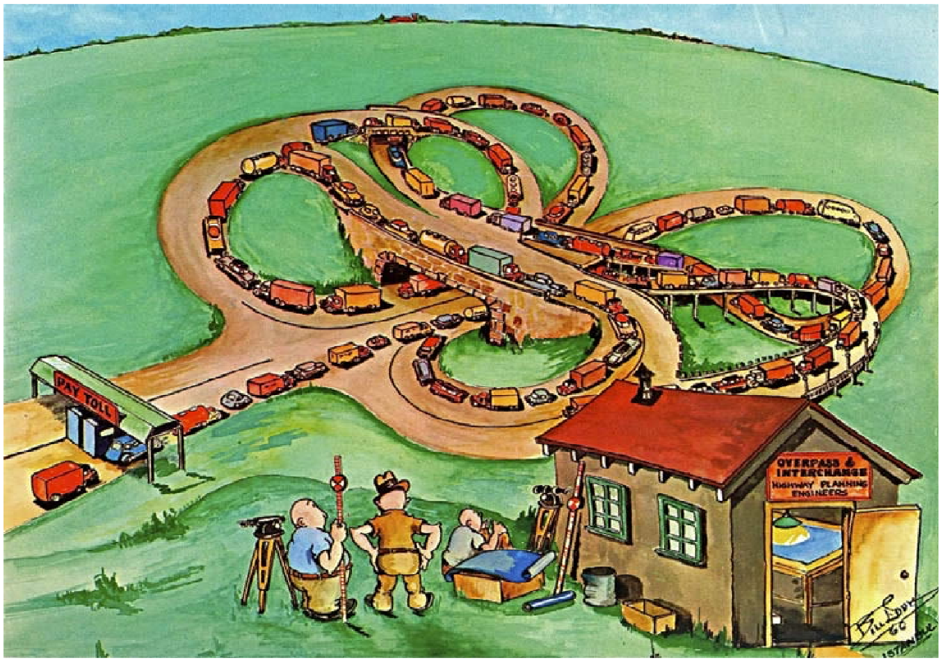
- Engineering the System: The overall development of a successful product that meets project challenges.

- Technical Integration: The integration of Design and Analysis, Hardware and Software, Operations, and Classical System Engineering along with interactions of Business, External Relations, Operating Environment and other functions to create a system with acceptable performance that is safe, reliable, and affordable.

Discussed was the challenge of space flight and the process whereby we can meet the challenge by Engineering the System. Technical Integration was seen as the overarching function that encompasses functions of Classical Systems Engineering, Design Analysis and Test, Manufacturing and Verification and Operations. A process for Technical Integration was defined that applies understanding of uncertainties, sensitivities, interactions and margins in trading requirements and attributes to achieve a balanced design. The trades and compromises are directed toward the goal of obtaining the best balance among performance, the -ilities, and affordability/cost while achieving necessary safety. Managing the design process was discussed with the conclusion that management and organization aspects are as complex as the design process itself.

Conclusion

Integration or not?



[Eddy, 1962]

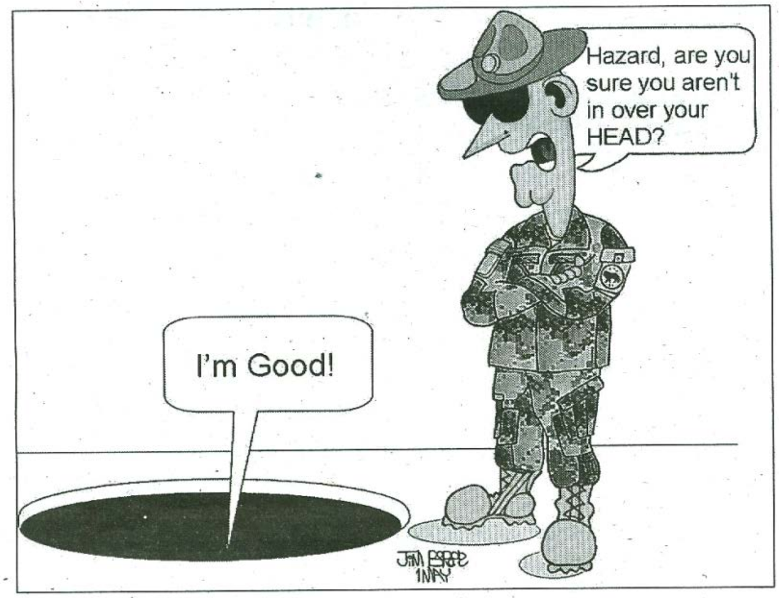
"This Is Something For The Home Office To Straighten Out"

No! This is something for engineering & project to solve by diligent planning, using a integration approach, based on uncertainties, sensitivities, interactions and risks.

Integration is everybody's job.

Figure 93. Does the Project Apply Engineering the System and Technical Integration?

Does the Project apply Engineering the System and Technical Integration? If not then the cartoon becomes our situation. Hopefully by applying the principles discussed in this report we won't get in over our heads.



[Pvt. Hazard by Jim Boroch]

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6. AUTHOR(S)	J.C. Blair, R.S. Ryan, and L.A. Schutzenhofer
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14. ABSTRACT

Approximately 80% of the problems encountered in aerospace systems have been due to a breakdown in technical integration and/or systems engineering. One of the major challenges we face in designing, building, and operating space systems is: how is adequate integration achieved for the systems' various functions, parts, and infrastructure? This Contractor Report (CR) deals with part of the problem of how we engineer the total system in order to achieve the best balanced design. We will discuss a key aspect of this question—the principle of Technical Integration and its components, along with management and decision making. The CR will first provide an introduction with a discussion of the Challenges in Space System Design and meeting the challenges. Next is an overview of Engineering the System including Technical Integration. Engineering the System is expanded to include key aspects of the Design Process, Lifecycle Considerations, etc. The basic information and figures used in this CR were presented in a NASA training program for Program and Project Managers Development (PPMD) in classes at Georgia Tech and at Marshall Space Flight Center (MSFC). Many of the principles and illustrations are extracted from the courses we teach for MSFC.

15. SUBJECT TERMS

technical integration, engineering the system, systems engineering, space systems design, verification and validation, lifecycle awareness, configuration management, natural environments, induced environments, sensitivity, margins, design phases

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National Aeronautics and
Space Administration
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George C. Marshall Space Flight Center
Huntsville, Alabama 35812